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DESIGN OF A CONTROLLER TO CONTROL LIGHT LEVEL IN A COMMERCIAL OFFICE

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Engineering

BY

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WRIGHT STATE UNIVERSITY
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November 20,2007

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY
SUPERVISION BY Saeid Javidbakht ENTITLED Design of a Controller to
Control Light Level in a Commercial Office BE ACCEPTED IN PARTIAL
FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of
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Abstract

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Proper amount of light in a business office is important for health and productivity of the employees. On a sunny day, there may be more than enough light entering the office from outside to carry out the necessary tasks. Presently, the main source of light in most offices is the fluorescent lamp. Thus, It is possible to save energy by dimming the fluorescent lamp. Dimming of the fluorescent lamp is possible by changing the frequency of the sinusoidal voltage or current. Hence, there is a need of a control system to adjust the light from the fixtures based on the light entering the office from outside. The design of a light control system is possible if the simulation of fluorescent lamp, the electronic ballast and the light sensor is available.

Presently, the number of light fixtures in a commercial office is based entirely on the activities performed in that office. No attention is paid to the outside light entering the office from windows. In this thesis, a fuzzy logic controller to dim the fluorescent lamp based on the availability of the outside light is presented. To carry out the design of a fuzzy controller, a Matlab-Simulink model based on the simulation of the complete light system is developed. The light system consists of an electronic ballast and a fluorescent lamp. The outside light is obtained from a light sensor installed on the frame of the window. The

fuzzy controller has two inputs: one is the output of the light sensor and the other is a reference frequency equivalent to maximum light level of the fluorescent lamp. The controller output controls the frequency of the electronic ballast. The rule-base of the fuzzy logic controller is developed based on the operation of the electronic ballast, the fluorescent lamp and the light sensor. Simulation was carried out with equally spaced five and seven fuzzy sets for the input and output. The fuzzy sets were then tweaked to take advantage of the piecewise linear control surface provided by the fuzzy logic controller. The simulation results show that dimming the fluorescent lamp can result in a substantial amount of energy saving and thus reduced the cost of utilities.

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1. Energy Consumption

1.1 Introduction to the problem

Nowadays, energy is one of the most important factors in people's life. Everyday, people deal with the price of energy and think about saving of energy in their life. Increase or decrease in the price of energy changes the strategic plans of all industries. Gasoline price change is shown during a period of 2002 to 2007 as an indicator of energy price in Figure 1.1.

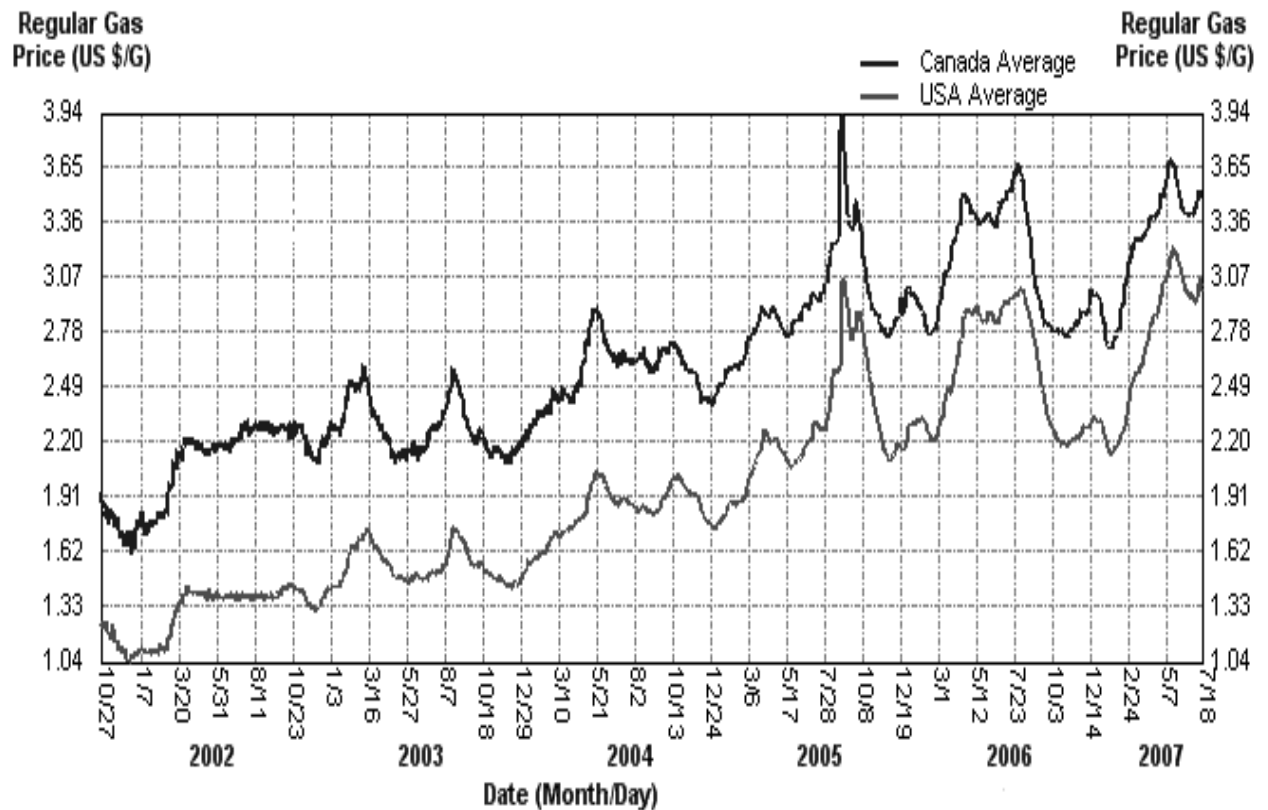


Figure 1.1 Gasoline prices (Energy Information Administration).

In a market economy, the price of energy such as oil, gas or electricity is driven by the principle of supply and demand which can cause sudden changes in the price of energy if either supply or demand changes. United States of America is by far the biggest consumer of energy in the world. The U.S. Department of Energy categorizes national energy use in four broad sectors: transportation, residential, commercial, and industrial. Energy usage in the transportation and residential sectors (about half of U.S. energy consumption) is largely controlled by individual consumers. Commercial and industrial energy expenditures are determined by businesses, government entities and other facility managers. National energy policy has a significant effect on energy usage across all four sectors.

As can be seen in Figure 1.2, sources of energy are coal, natural gas, crude oil, nuclear electric power, renewable energy, petroleum and other small sources. Also, Figure 1.2 shows the sources and contribution of energy sectors in the United States. It can be seen from this figure that industrial demand is the biggest part of the used energy followed by transportation sector. Energy usage for residential and commercial sectors together is about half of total demand. Price of energy in the world depends on the price of oil and when price of oil increases, the price of electricity goes up.

1.2 Residential sector

The residential sector refers to all private residences, including single-family homes, apartments, manufactured homes and dormitories. Energy usage

in this sector varies significantly across the country, due to regional climate differences and different regulation.

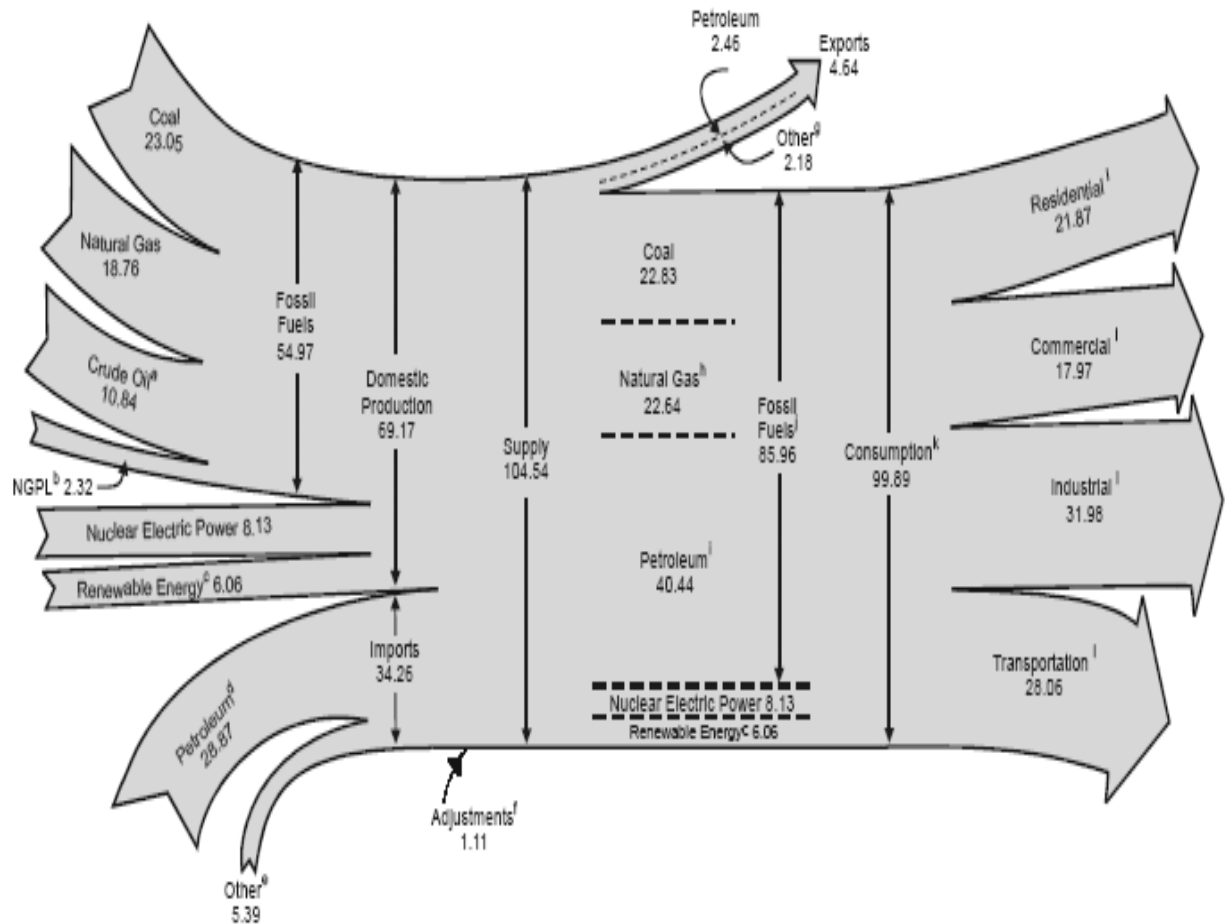


Figure 1.2 Energy conversion in the U.S.A. (Wikipedia. encyclopedia)

On an average, about half of the energy used in the U.S. homes is expended on space conditioning (i.e. heating and cooling). The efficiency of furnaces and air conditioners has increased steadily since the energy crises of the 1970s. The 1987 National Appliance Energy Conservation Act authorized the Department of Energy to set minimum efficiency standards for space conditioning equipment and other appliances each year, based on what is "technologically

feasible and economically justified". Beyond these minimum standards, the Environmental Protection Agency (EPA) awards the Energy Star designation to appliances that exceed industry efficiency averages by an EPA-specified percentage.

Despite technological improvements, many American lifestyle changes have put higher demands on heating and cooling resources. The average size of homes built in the United States has increased significantly, from 1500 ft² in 1970 to 2300 ft² in 2005. The single-person household has become more common, as has central air conditioning: 23% of households had central air conditioning in 1978, that figure rose to 55% by 2001.

As a cheaper alternative to the purchase of a new furnace or air conditioner, most public utilities encourage smaller changes that the consumer can make to lessen space conditioning usage. Weatherization is frequently subsidized by utilities or state/federal tax credits, as are programmable thermostats. Consumers have also been urged to adopt a wider indoor temperature range (e.g. 65 °F in winter, 80 °F in summer).

1.2.1 Home energy consumption averages

Energy consumption average for a typical home in the United States is divided to:

- space conditioning, 44%
- water heating, 13%
- lighting, 12%

- refrigeration, 8%
- home electronics, 6%
- laundry appliances, 5%
- kitchen appliances, 4%
- other uses, 8%

Energy usage in some homes may vary widely from these averages. For example, milder regions such as the southern U.S. and pacific coast of the USA need far less energy for space conditioning than New York City or London. In milder climates, lighting energy may easily consume up to 40% of total energy. Certain appliances such as a waterbed, hot tub, or pre-1990 refrigerator use significant amounts of electricity. In most residences, no single appliance dominates, and any conservation efforts must be directed to numerous areas in order to achieve substantial energy savings. However, ground source heat pump systems are the most energy efficient, environmentally clean, and cost-effective space conditioning systems available (Environmental Protection Agency), and can achieve reductions in energy consumptions of up to 70%.

1.3 Commercial sector

The commercial sector consists of retail stores, offices (business and government), restaurants, schools and other workplaces. Energy in this sector has the same basic end uses as the residential sector, in slightly different proportions. Space conditioning is again the single biggest consumption area, but

it represents only about 30% of the energy use of commercial buildings. Lighting, at 25%, plays a much larger role than it does in the residential sector. Lighting is also generally the most wasteful component of commercial use. A number of case studies indicate that more efficient lighting and elimination of over-illumination can reduce lighting energy by approximately fifty percent in many commercial buildings.

Commercial buildings can greatly increase energy efficiency by thoughtful design for heating , cooling and lighting control. Commercial buildings often have professional management, allowing centralized control and coordination of energy conservation efforts. As a result, fluorescent lighting (about four times as efficient as incandescent) is the standard for most commercial space, although it produces certain adverse health effects. As most buildings have consistent hours of operation, programmed thermostats and lighting controls are common.

However, too many companies believe that merely having a computer controlled building automation system guarantees energy efficiency. As an example, one large company in Northern California boasted that it was confident that its state of the art system had optimized space heating. A more careful analysis by Lumina Technologies showed that the system had been given programming instructions to maintain constant 24 hour temperatures in the entire building complex. This instruction caused the injection of night time heat into vacant buildings when the daytime summer temperatures would often exceed 90 degrees of fahrenheit. This mis-programming was costing the company over \$130,000 per year in wasted energy (Lumina Technologies, 1997). Many

corporations and governments also require the Energy Star rating for any new equipment purchased for their buildings.

Solar heat loading through standard window designs usually leads to high demand for air conditioning in summer months. An example of building design overcoming this excessive heat loading is the Dakin Building in Brisbane, California, where fenestration was designed to achieve an angle with respect to sun incidence to allow maximum reflection of solar heat; this design also assisted in reducing interior over-illumination to enhance worker efficiency and comfort. Artificial lighting consumes a significant part of all energy consumed worldwide. In homes and offices from 20 to 50 percent of total energy consumed is due to lighting.

Most importantly, for some buildings over 90 percent of lighting energy consumed can be an unnecessary expense through over-illumination. Thus lighting represents a critical component of energy use today, especially in large office buildings where there are many alternatives for energy utilization in lighting. There are several strategies available to minimize energy requirements in any building.

- Specification of illumination requirements for each given use area.
- Analysis of lighting quality to insure that adverse components of lighting (for example, glare or incorrect color spectrum) are not biasing the design.
- Integration of space planning and interior architecture (including choice of interior surfaces and room geometries) to lighting design.
- Design of time of day use that does not expend unnecessary energy.

- Selection of fixture and lamp types that reflect best available technology for energy conservation.
- Training of building occupants to utilize lighting equipment in most efficient manner.
- Maintenance of lighting systems to minimize energy wastage.

It can be seen that lighting design plays a important role in minimizing of the energy consumption. Specification of illumination requirements is the basic concept of deciding how much illumination is required for a given task. Clearly, much less light is required to illuminate a hallway or bathroom compared to that needed for a word processing work station. Prior to 1970 (and even today), a lighting engineer would simply apply the same level of illumination design to all parts of the building without considering usage. Generally speaking, the energy expended is proportional to the design illumination level. For example, a lighting level of 80 footcandles might be chosen for a work environment involving meeting rooms and conferences, whereas a level of 40 footcandles could be selected for building hallways. If the hallway standard simply emulates the conference room needs, then twice the amount of energy will be consumed as is needed for hallways. Unfortunately, most of the lighting standards even today have been specified by industrial groups who manufacture and sell lighting, so a historical commercial bias exists in designing most building lighting, especially for office and industrial settings. Beyond the energy factors being considered, it is important not to over design illumination, lest adverse health effects such as

headache frequency, stress, and increased blood pressure be induced by the higher lighting levels. In addition, glare or excess light can decrease worker efficiency.

So, lighting design can be one of the important factor in saving of energy. The other factor which can be important in energy saving is controlling of the light level in the building based on the amount of light required for the work station in a commercial building .

Everyday, when we enter a big building, we can see a lots of lamps that are on during the day and in some buildings we can see some lamps which are on 24 hours seven days a week. Sometimes, there is no body in the building but all the lamp are on. In some buildings the lamps close to the window are on in a sunny day that light from outside illuminates inside of the office. We can see in most commercial buildings, some offices where lamps are on when people generally leave their office without turning off the lamps .

Let us look at an example of a commercial building. The main lighting lamps for the commercial building is fluorescent and compact fluorescent lamps. Suppose there is a four-floor building and eighty offices on each floor. On an average, there are three fixtures per office and the number of fluorescent lamps per fixture is also three. Corridor on each floor has about 200 fixtures with four fluorescent lamps. With a load calculation only for lighting, there are 720 lamps per floor and total of 2880 lamps for building. The average wattage of the fluorescent lamps is 50 watt and thus the total light load for building is about

150kw. On the corridor there are 200 fixtures with 4 lamps per fixture. The total lamps for four floors are 3200 lamps and the light wattage would be 160kw.

It is assumed that the average hours that an office is open or occupied would be 12 hours per day, and for corridor 24 hours per day. Monthly energy consumption in kilowatt hours for this building is 169,200 kwh. In Dayton, Ohio the price is about 7 cent per kilo watt hour and with this price, the cost of lighting for this example is about 12,000 dollars per month and 144,000 dollars per years. The energy consumption and hence the cost of energy is high and should not be neglected . The question is : what can be done to reduce these numbers? First of all, the method of usage and demand for the offices should be corrected. In this example, the average of 12 hours per day is taken for lamps in on state. An automatic light control system can turn off lamps based on occupation of offices and the consumption time will be decreased. Every office has window or windows and the level of light should be kept at a proper level based on lighting standard table. A light control system, is able to control the light level based on light from outside and decrease the light level of fluorescent lamp if the light level in office is more than proper value (Daylight Harvesting). The energy consumption can be reduced by controlling the light level. In the pervious example, the total lighting load was 169200 kwh, and let us assume that the light from outside is able to increase the light level in a typical office by 20%. For this example, it is possible to reduce the lighting load by 20%, i.e, 33840 Kwh. For corridors, it is possible to put all fluorescent lamp in minimum light from 8 P.M. to 6 A.M because there is nobody in the building. Presently, the main source of light

in most offices is the fluorescent lamp. It is possible to save energy by dimming the fluorescent lamp. Dimming of the fluorescent lamp is possible by changing the frequency of the sinusoidal voltage or current hence, there is a need for a control system, which is able to control the light level of fluorescent lamp. In other word, we need to design a controller that is able to dim fluorescent lamp when outside light enters the office from the window or windows. The outside light comes in and increases the light level in the office. A controller is able to dim fluorescent lamp and set up the fluorescent lamp light in proper light level.

1.4 Outline of Thesis

In this thesis, the design of a simple low cost lighting control system for a typical office with fluorescent lamps is presented. The light control system components and operation are explained in chapter 2. The complete fluorescent lamp system (fluorescent lamp, electronic ballast) along with a light sensor simulation is carried out in chapter 3 based on the experimental data for voltage, current and power. Experimental data is plotted and the Levenberg-Marquardt algorithm (LMA) curve fitting method is used to fit the best mathematical equation to experimental data. The mathematical equation for the fluorescent lamp is obtained and the Matlab-Simulink model of the fluorescent lamp is carried out based on the mathematical model. The simulation of the electronic ballast is performed using a typical half-bridge series-resonant circuit with parallel load. The components values are calculated based on the operation of the ballast above resonance frequency. The Matlab-Simulink model for electronic ballast is

developed, and the electronic ballast model is connected to the fluorescent lamp model. The electronic circuit of a typical light sensor is obtained and the simulation of the light sensor using the resistance-light characteristic is carried out. The complete simulation model including all the components is carried out and simulation results are obtained.

The basic fuzzy set theory needed to support fuzzy controller design and calculation is presented in chapter 4. Based on the light system simulation and behavior, a proportional fuzzy logic controller is designed considering the outside light entering the office. The Matlab-Simulink programs and models for fuzzification and defuzzification are carried out and fluorescent light control system response is obtained for five and seven fuzzy sets input and output. The fuzzy sets are tuned experimentally to improve the response of the light control system.

The results of simulation are presented in chapter 5 and chapter 6 provides conclusions and recommendation for the future work followed by the appendices and bibliography.

2. Light control system components and operation

2.1 Introduction

It was explained in the last chapter, that a light control system is able to control the light level in an office based on the light from outside. The light control system should decrease the light level of fluorescent lamp if the light level is more than the proper value and increases it if the office needs more light. Thus, the energy consumption can be reduced by controlling the light level. General speaking, light level control or dimming of a fluorescent lamp is possible by controlling the frequency of the electronic ballast. Therefore, it is necessary to know how a fluorescent lamp works and how an electronic ballast works as the driver circuit of the fluorescent lamp. The light sensor principle of operation is also explained later in the chapter. In this chapter, in all current and voltage figures, the time unit is second, current unit is ampere and voltage unit is volt.

2.2 Fluorescent Lamp

2.2.1 Principles of Operation

A linear fluorescent lamp or compact fluorescent lamp (CFL) consists of a glass tube containing a low-pressure gas (such as Mercury Argon or Krypton) and a tungsten filament at each end. The principle of operation of a fluorescent tube is based on the inelastic scattering of electrons. An incident electron

(emitted from the coils of wire forming the cathode electrode) collides with an atom in the gas (such as mercury, argon or krypton) used as the ultraviolet emitter. This causes an electron in the atom to jump up temporarily to a higher energy level to absorb some, or all, of the kinetic energy delivered by the colliding electron. This is why the collision is called “ inelastic ” as some of the energy is absorbed.

This higher energy state is unstable, and the atom emits a photon as the atom's electron reverts to a lower, more stable, energy level. The photons that are released from the chosen gas mixtures tend to have a wavelength in the ultra-violet part of the spectrum. Since the ultra-violet spectrum is not visible to the human eye, the fluorescent is used to convert this into visible light. This fluorescent conversion occurs in the phosphor coating on the inner surface of the fluorescent tube, where the ultra-violet photons are absorbed by electrons in the phosphor's atoms, causing a similar energy jump and absorb for emission of the further photon.

The photon that is emitted from this second interaction has a lower energy level than the one that caused it. The chemicals that make up the phosphor are specially chosen so that these emitted photons are at wavelengths visible to the human eye. The difference in energy between the absorbed ultra-violet photon and the emitted visible light photon goes to heat up the phosphor coating.

A fluorescent lamp bulb is filled with a gas containing low pressure mercury vapor and argon (or xenon) or more rarely argon-neon or sometimes

even krypton. The inner surface of the bulb is coated with a fluorescent paint made of varying blends of metallic and rare-earth phosphor salts.

The bulb's cathode is typically made of coiled tungsten which is coated with a mixture of barium, strontium and calcium oxides (chosen to have a relatively low thermionic emission temperature).

2.2.2 How does a fluorescent lamp turn on?

When the light switch is turned on, the electric power heats up the cathode enough for emitting of electrons. These electrons collide with and ionize noble gas atoms in the bulb surrounding the filament to form a plasma by a process of impact ionization. As a result of avalanche ionization, the conductivity of the ionized gas rapidly rises and allowing higher currents to flow through the lamp. The mercury, which exists at a stable vapour pressure equilibrium point of about one part per thousand in the inside of the tube (with the noble gas pressure typically being about 0.3% of standard atmospheric pressure), is then likewise ionized, causing it to emit light in the ultraviolet (UV) region of the spectrum predominantly at wavelengths of 253.7 nm and 185 nm. The UV light is absorbed by the bulb's fluorescent coating, which re-radiates the energy at lower frequencies (longer wavelengths) to emit visible light. The blend of phosphors controls the color of the light, and along with the bulb's glass prevents the harmful UV light from escaping. A typical linear fluorescent lamp is shown in Figure 2.1.

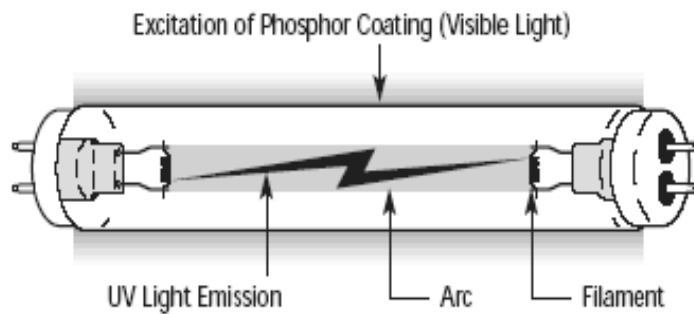


Figure 2.1 Typical linear fluorescent lamp.

When the lamp is turned on, the voltage across the lamp is not sufficient to continue the initial ionization of the vapor (mercury). This happens because of a cold filaments on both side of the lamp but after a short time the filaments on both sides heat up and the electrons spread out to the vapor. Higher voltage helps to reduce warm up time of the filaments. A higher voltage is provided by a capacitor, which is placed parallel to the lamp. This capacitor is a part of electronic ballast. Once the gas in the tube is ionized, visible light can be seen but there is a problem. Fluorescent lamps are negative resistance devices, so as more current flows through them (more gas ionized), the electrical resistance of the fluorescent lamp drops, allowing even more current to flow. Connecting of fluorescent lamp directly to a constant-voltage power line, can be self-destructing due to the uncontrolled current flow. To prevent this, fluorescent lamps must use an auxiliary device, commonly called a ballast, to regulate the current flow through the tube. The voltage–current characteristic of a linear fluorescent lamp is shown in Figure 2.2.

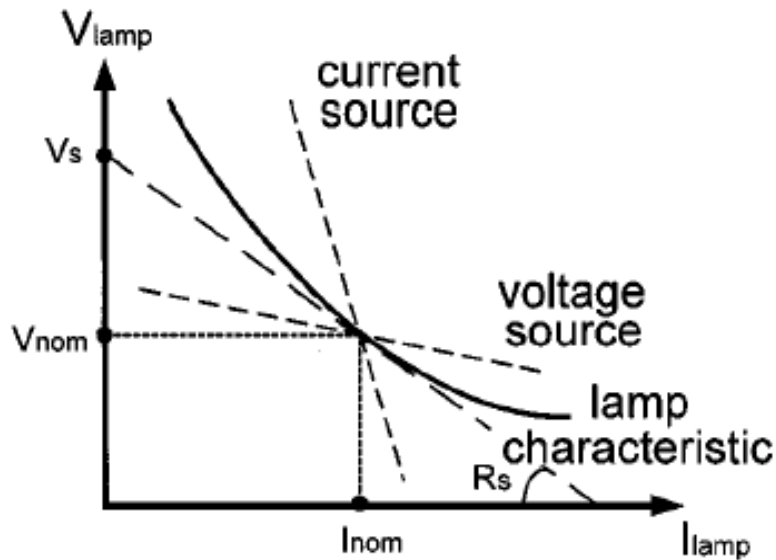


Figure 2.2 Voltage-current characteristic of a linear fluorescent lamp.

2.3 Ballast

Ballasts are most commonly used with an electrical circuit or a device that presents a negative resistance to the supply. If a device with negative resistance is connected to a constant-voltage power supply, it would draw an ever-increasing amount of current until it is destroyed or causes the power supply to fail. To prevent this problem, a ballast provides a positive resistance or reactance that limits the ultimate flow of current to an appropriate level. The following section gives a brief description of the commonly used ballasts.

2.3.1 Resistors Ballasts

One type of resistor ballasts is the fixed resistors ballast that can be used in low-powers loads like a neon lamp. Because of high resistance of the ballast, it

dominates the flow of current in the circuit even in the face of negative resistance introduced by the lamp.

The other type of resistor ballast is self-variable resistor ballast. This ballast has the property of increasing the resistance when the current increases, and decreasing the resistance as current decreases. Physically, these devices are often built quite like incandescent lamps like the tungsten filament of an ordinary incandescent lamp. If the current increases, the ballast resistor gets hotter and its resistance goes up, and the voltage drop increases. If the current decreases, the ballast resistor gets colder, its resistance drops, and the voltage drop decreases. Therefore, the ballast resistor tends to maintain a constant current flowing through it despite the variations in applied voltage or changes in the rest of an electric circuit.

2.3.2 Reactive or Conventional Ballasts

In all type of resistor ballasts, the current flows through the resistor and causes a lost of power. Because of the power that would be lost, resistors ballast are not used for lamps of more than a watt or two. In an ideal or theoretically perfect reactance, no power would be lost while limiting the current flow; however, losses due to resistance can only be minimized, not eliminated entirely.

An inductor is very common in reactive or conventional ballasts to provide the proper starting and operating electrical condition to power a fluorescent lamp, neon lamp, or high intensity discharge (HID) lamp. (Because of the use of the

inductor, such ballasts are usually called magnetic ballasts.) The inductor has two benefits:

1. Its reactance limits the power available to the lamp with only minimal power losses in the inductor.
2. The voltage spike produced when current through the inductor is rapidly interrupted is used in circuits to first strike the arc in the lamp.

One of disadvantages of the inductor is that current is shifted out of phase with the voltage, producing a low power factor. In some ballasts, a capacitor is often added up with the inductor to correct the power factor. The ballasts that control two or more lamps, commonly use different phase relationships between the multiple lamps. This not only reduces the flicker of the individual lamps, it also helps maintains a high power factor. These ballasts are often called lead-lag ballasts because the current phase in one lamp leads the power source phase and the current phase in the other lamp lags the power source phase.

As it is shown in Figure 2.3, for conventional ballast, the lamp needs a starter to provide a high voltage across the lamp to start ionization. The starter with a small gap between its two contacts provides this high voltage. There are two contact strips in the starter, one normal and one bimetallic, which are normally open and enclosed in a glass envelope filled with the inert gas. When

voltage is applied to the circuit, it is not sufficient to cause spontaneous ionization of the gas in the tube, and the lamp remains in high impedance state (not turn on).

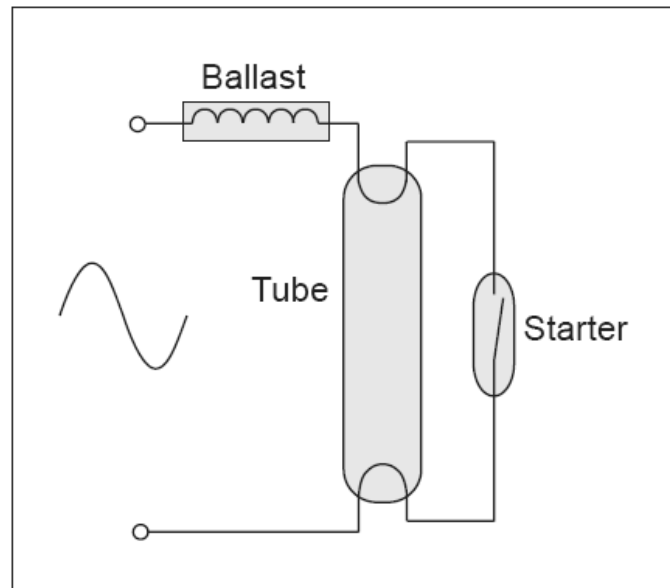


Figure 2.3 Simple conventional lamp ballast.

However, the electric field that the voltage creates in the small gap between the contacts in the starter is sufficient to ionize the gas there. This allows a current to flow in the metal strips and through the gas (and also through the filaments of lamp which heats them and facilitates the subsequent ionization). The heat generated by the current flows through the gas causes the bimetallic strip to bend towards the others. When the contacts finally touch, two things occur: firstly, the gas in the starter de-ionizes and the bimetallic strip begins to cool. Secondly, as the impedance of the circuit falls, the current through the ballast inductor and the filaments of the lamp increases. A few tenths of a second later, the bimetallic strip cool sufficiently to bend back slightly, reopening the gap.

The sudden increase in impedance and consequent sharp reduction in inductor causes a large over voltage across the inductor. Given the correct condition, this over voltage is large enough to cause ionization of the gas in lamp. At this point the impedance of the fluorescent lamp falls to a minimum, and the voltage drop across it falls to a level below that required ionizing of the gas in the starter contact gap. The contacts thus remain open until the lamp is next turned on. However there are a few problems with this type of ballast:

1. False starts

Since there is no synchronization with the main input, the starter operates at a random time on the current waveform, the contacts opening at an inductor current level anywhere between zero and the maximum. This means the over voltage generated may not be large enough to cause ionization of the gas in the tube. If this the case, the process repeats itself until full ionization occurs, causing the "flashing" commonly seen at start up of conventional fluorescent ballasts.

2. Physical problems

There are also physical problems with this type of ballast. At zero cross point of the current in each 50/60HZ cycle, the gas in the tube de-ionizes. For a short period of time, there is not any ionized gas atom to hit to inner surface of fluorescent lamp and result is flicker in a 50/60HZ. This can cause disturbing "stroboscopic" optical effects with moving machinery. In industrial plants,

fluorescent tubes are used in pairs in a single light fixture, each lamp being fed from different phases, either real or virtual via a capacitor. This help to eliminate flickering observed by human eye.

In the USA and all country with voltage of 120 volt, the voltage is not sufficient for the larger lamps to strike and maintain an arc in the fluorescent lamp and an autotransformer is used to step-up the voltage. The autotransformer is designed with enough leakage inductance so that the current flow is appropriately limited. Because of the large inductors and capacitors that must be used, reactive ballasts operated at the frequency of 60HZ tend to be large and heavy and also, They commonly produce acoustic noise (frequency hum).

Figure.2.4 shows a typical magnetic ballast for the fluorescent lamps. The top is a high- power factor, lead-lag ballast for two 30-40W lamps, the middle is a low power factor ballast for a single 30-40W lamp while the bottom ballast is a simple inductor used with a 15W preheat lamp.



Figure 2.4 Conventional ballasts(Philips lighting Company).

2.3.3 Electronic Ballasts

An electronic ballast uses solid state electronic circuit to provide the proper starting and operating electrical condition to power one or more fluorescent lamps and more recently HID (High-Intensity Discharge) lamps. Electronic ballasts usually change the frequency of the power from the standard mains frequency to 20,000 Hz or higher, substantially eliminating the stroboscopic effect of flicker (100 or 120 Hz, twice the line frequency) associated with fluorescent lighting. In addition, because more gases remains ionized in the arc stream, the lamps actually operate at about 9% higher efficiency above approximately 10 kHz. Lamp efficiency increases sharply at about 10 kHz and continues to improve until approximately 20 kHz. Because of the high frequency of operation, electronic ballasts are generally smaller, lighter, and more efficient (and thus run cooler) than line frequency magnetic ballasts.

The higher operating frequency means that it is often practical to use a capacitor as the current-limiting reactance rather than the inductor required at original frequency of electrical network. Because of physical structure, capacitors tend to be much lower in losses than inductors, allowing them to more closely approach an "ideal reactance". Electronic ballasts are often based on inverter/converter style switched-mode power supplies, first rectifying the input power and then chopping it at a high frequency. The main electronic part of all electronic ballasts is a series resonant circuit. This resonant circuit is a class D RF resonant amplifier and also called class D dc-dc inverter.

One of the application of class D RF resonant amplifier is in electronic ballasts. Class D RF resonant amplifier is fed by a dc voltage source and employ a series-resonant circuit or a resonant circuit that is derived from series-resonant circuit. If the load quality factor is sufficiently high, the current through the resonant circuit is sinusoidal and current through the switches are half-wave sinusoid. The voltage across the switches are square wave.

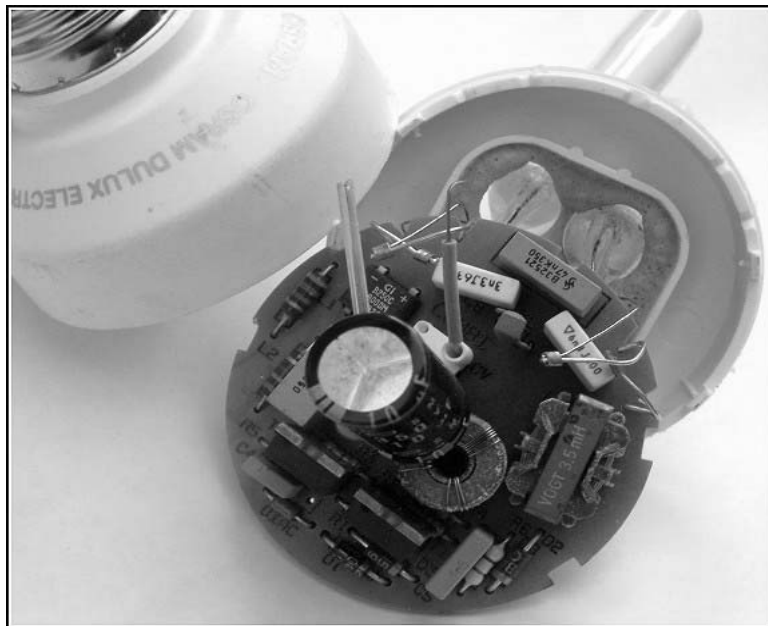


Figure 2.5 Electronic ballasts (Osram Sylvania Company).

Electronic ballast manufacturer are using two common type of class D RF series resonant to make the electronic ballast : Class D voltage source half bridge and class D voltage source full bridge with series resonant circuit. There are two switches on half bridge class D voltage source amplifier. The class D RF amplifier employs MOSFET technology switches to chop and invert input DC voltage. These switches are connected to the circuit with three terminals : gate,

source and drain. Gate pulse waveform is able to connect and disconnect switch based on the frequency of the gate source voltage.

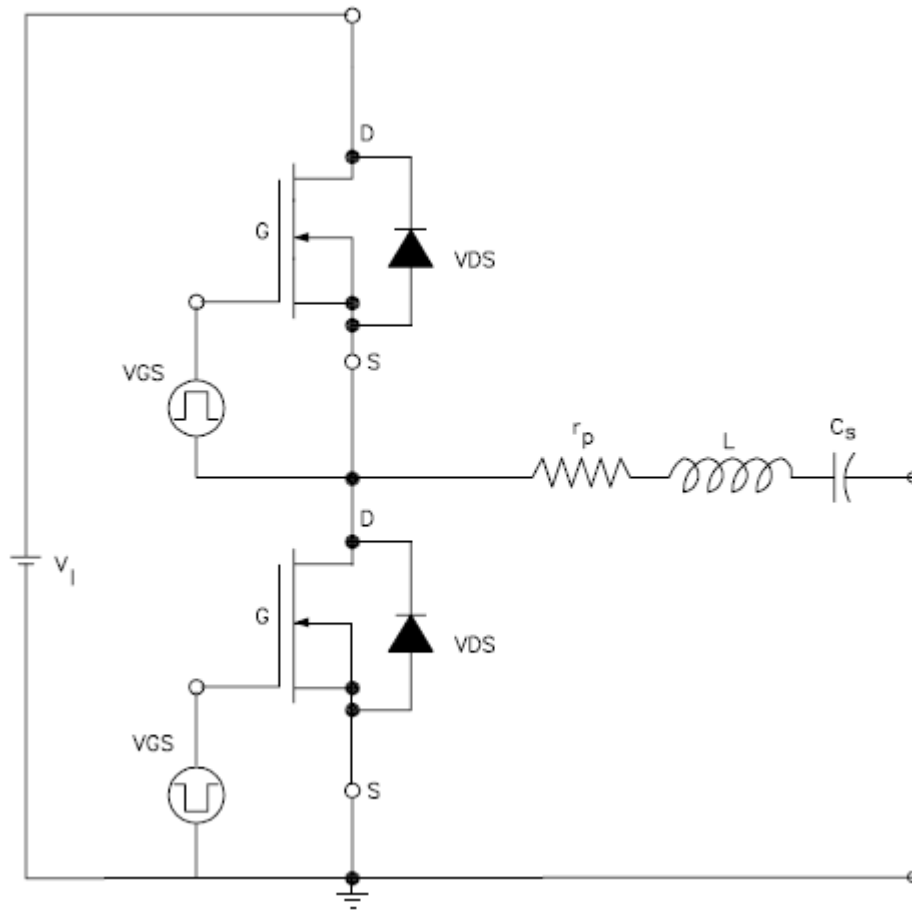


Figure 2.6 Electronic ballast circuit.

Figure 2.6 shows a typical class D voltage source RF series resonant amplifier that is used in most electronic ballast for fluorescent lamps. The Dc voltage (V_I) is provided by a full bridge rectifier circuit that it is not shown in the figure. The AC voltage from the main power supply is applied to the input of a full bridge AC-DC rectifier circuit. The output of the AC-DC rectifier circuit (V_I) is used for switching network of electronic ballast. The V_{GS} (Gate-Source voltage of the

switch) waveform for both the switches is the same but one of them is the inverse of the other. Gate-source voltage of the switches should be large enough to be able turn on the switches. During the positive part of the waveform which is a square wave , the switches turn on during the negative part of the waveform turn off. It is possible to connect and disconnect switches based on frequency of the VGS wveforand also, resulting in a square waveform of the switching network. The positive part of the waveform comes from the upper switch and negative part comes from the lower switch. As shown in the Figure 2.7, it can be seen from this figure that the frequency of the output waveform is almost the same as the frequency of VGS waveform.

The class D RF resonant amplifier can oscillate when specific value is chosen for the resistor, inductor and capacitor. (r_P L, C_s). The proper values for these components are related to each other with a quality factor. The quality factor for a series resonant circuit is defined by $Q_L = (\sqrt{\frac{L}{C}}) / R$. A system with Q_L less than or equal to 1/2 cannot be described as oscillating at all, instead the system is said to be in an over-damped ($Q_L < 1/2$) or critically damped ($Q_L = 1/2$) state. However, if $Q_L > 1/2$, the system's amplitude oscillates, while simultaneously decaying exponentially. For a class D RF resonant circuit, the quality factor should be more than 2.5 to make sure the amplifier oscillate and a sine wave is be produced. The class D RF amplifier principle of operation is explained by the waveforms sketched in the Figure 2.7.

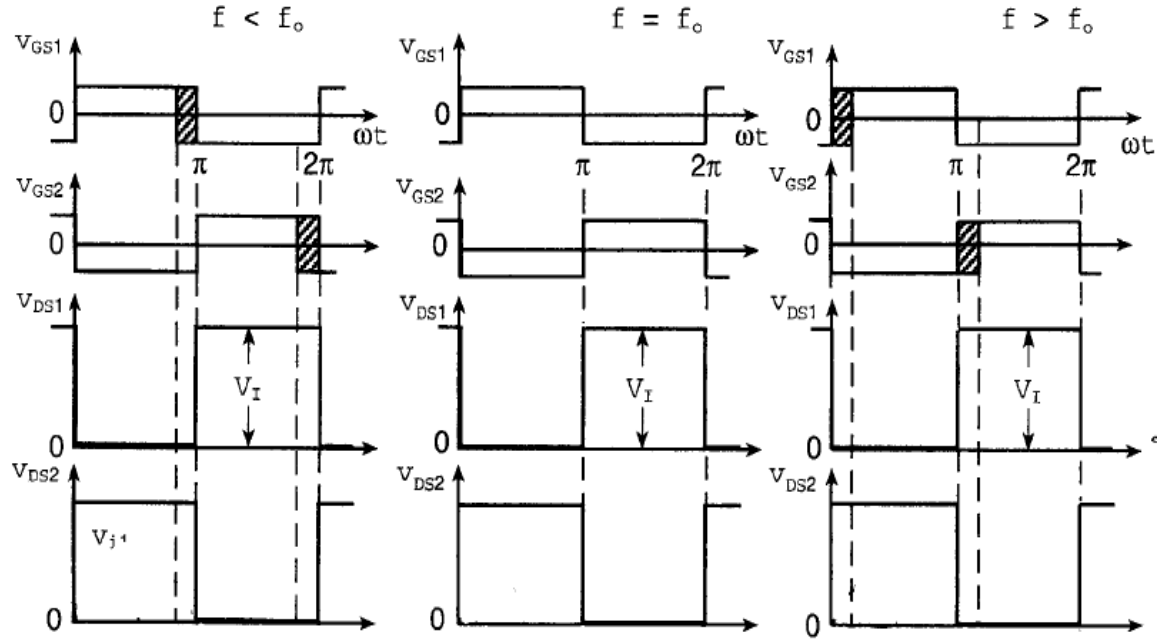


Figure 2.7 Output voltage waveforms of switching network.

For class D RF the voltage at the input of the series-resonant circuit is a square waveform with a magnitude of V_i . If the load quality factor Q_L for series resonant circuit is high enough, the current through this circuit is nearly a sine wave.

In case of $f = f_0$, the switches turn on and off at zero current, resulting in zero switching losses and high efficiency. In many application, the operating frequency f is not equal to the resonant frequency $f_0 = 1/(2\pi\sqrt{L/C})$ because the output power or the output voltage is often controlled by varying the operating frequency of f . Figure 2.7 shows that switches losses are least if the amplifier frequency is equal to the resonant frequency f_0 . For application like electronic ballast if ballast is designed for operation for a fixed frequency, the best

frequency is the resonant frequency of f_0 but for other case, some power is lost because of non-zero switching of the switches.

For electronic ballast based on class D RF resonant amplifier, there is a problem with power factor (like the conventional ballast) and EMI reduction (electromagnetic interference). Electronic ballasts operate at a higher frequency than the main source therefore; electronic ballast transmits EMI back to the supply. Also, most ballast draws a non-sine wave current from the main supply unlike an incandescent bulb. To satisfy the requirements of the power factor, the manufacturers use a simple passive filter to correct the power factor of the ballast.

2.4 Light Sensor

A light sensor is a sensor that measures the amount of light that it sees and reports the amount of light as a number or as an output signal. The main part of a light sensor is a photoresistor whose resistance decreases with increasing incident light intensity as shown in Figure 2.8.

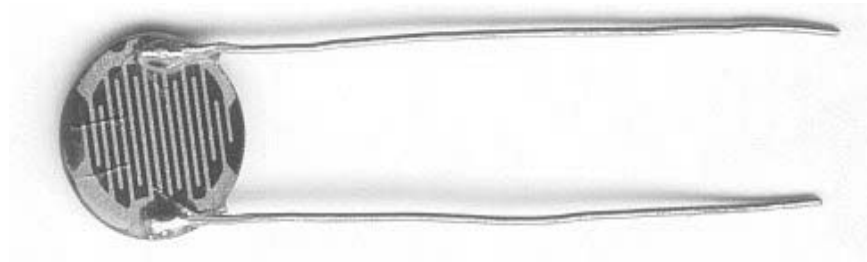


Figure 2.8 Light-dependent resistor (LDR).

A photoresistor is made from a high-resistance semiconductor. If light falling on the device is high, photons absorbed by the semiconductor give enough energy to the bound electrons to jump into the conduction band. The resulting free electron (and its hole pair) conduct electricity, thereby lowering resistance.

A photoelectric device can be either intrinsic or extrinsic. An intrinsic semiconductor has its own charge carriers and is not an efficient semiconductor, e.g. silicon. In intrinsic devices, the only available electrons are in the valence band and hence the photon must have enough energy to excite the electron across the entire band gap. Extrinsic devices have impurities added to the silicon, which have a ground state energy closer to the conduction band. Since the electrons do not have as far to jump, lower energy photons (i.e. longer wavelengths and lower frequencies) are sufficient to trigger the device. If a sample of silicon has some of its atoms replaced by phosphorus atoms (impurities), there will be extra electrons available for conduction. This is an example of an extrinsic semiconductor.

Cadmium sulphide (CdS) cells rely on the material's ability to vary its resistance according to the amount of light striking the cell. The more light that strikes the cell, the lower the resistance. Although not accurate, even a simple CdS cell can have a wide range of resistance from less than 100 Ω in bright light to an excess of 10 M Ω in darkness. The cells are also capable of reacting to a broad range of frequencies, including infrared (IR), visible light, and ultraviolet

(UV). They are often found on street lights as automatic on/off switches. They are even used in heat-seeking missiles to sense the targets.

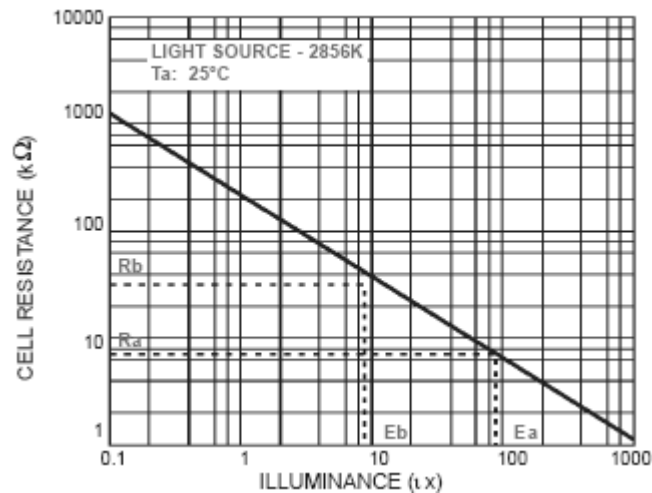


Figure 2.9 Resistance-light characteristic of the light-dependent resistor (LDR) (Selco products company).

Inexpensive cadmium sulphide cells can be found in many consumer items such as camera light meters, clock radios, security alarms, street lights and outdoor clocks. However, on the other end of the scale, GeCu photoconductors are among the best infrared detectors available, and are used for infrared astronomy and infrared spectroscopy.

2.5 Fluorescent light principal of operation

A simple dimmable fluorescent lamp circuit and ballast is shown in Figure 2.10. A small square waveform VGS, applied at the gate of the switching network produces a square waveform of the same frequency at the output of the switching network as shown in figure 2.11. This voltage is applied to the resonant RLC circuit of electronic ballast and a sine wave of the same frequency is

produced at the output of the electronic ballast as shown in Figure 2.12. It is important to note that the frequency applied to the lamp from electronic ballast can be controlled by the gate voltage V_{GS} .

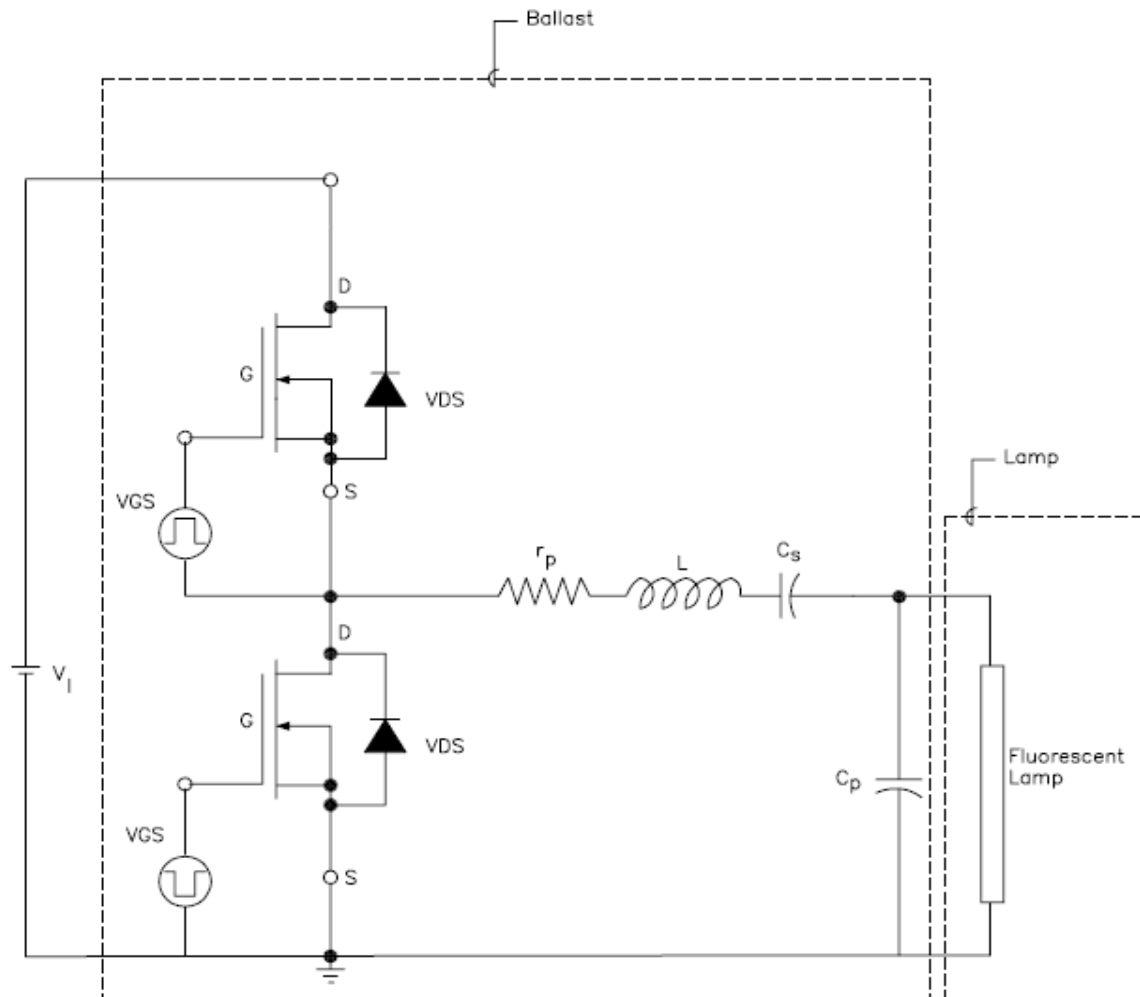


Figure 2.10 Complete fluorescent lamp circuit.

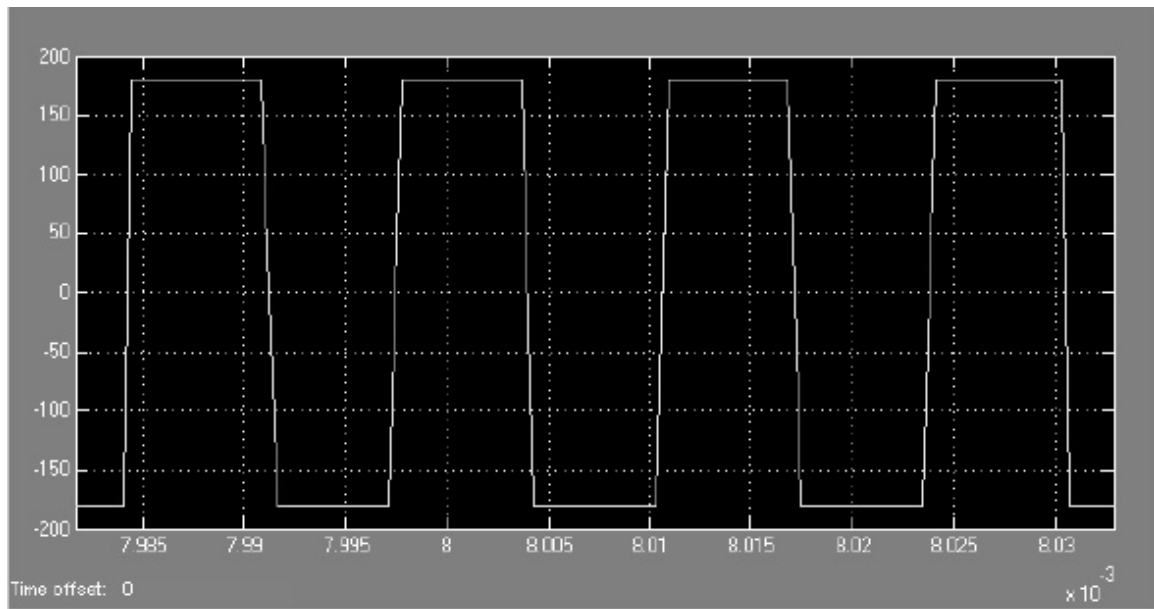


Figure 2.11 Square wave on the output of switching network.

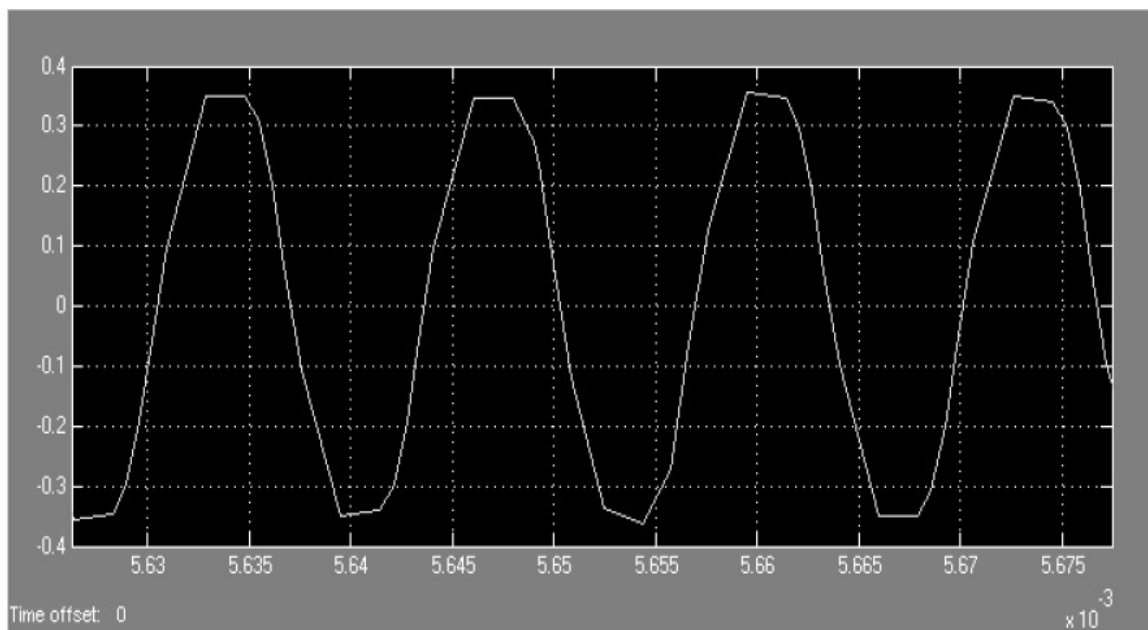


Figure 2.12 Fluorescent lamp current waveform in 75 khz.

Any change in the frequency of the VGS causes that the impedance of RLC resonant circuit is changed. By this way, it is possible to control fluorescent lamp current by change of the switching frequency. The current waveform for the

fluorescent lamp in 75 KHz is shown in Figure 2.12. Figure 2.13 shows the current waveform of the same lamp in the 91 kHz.

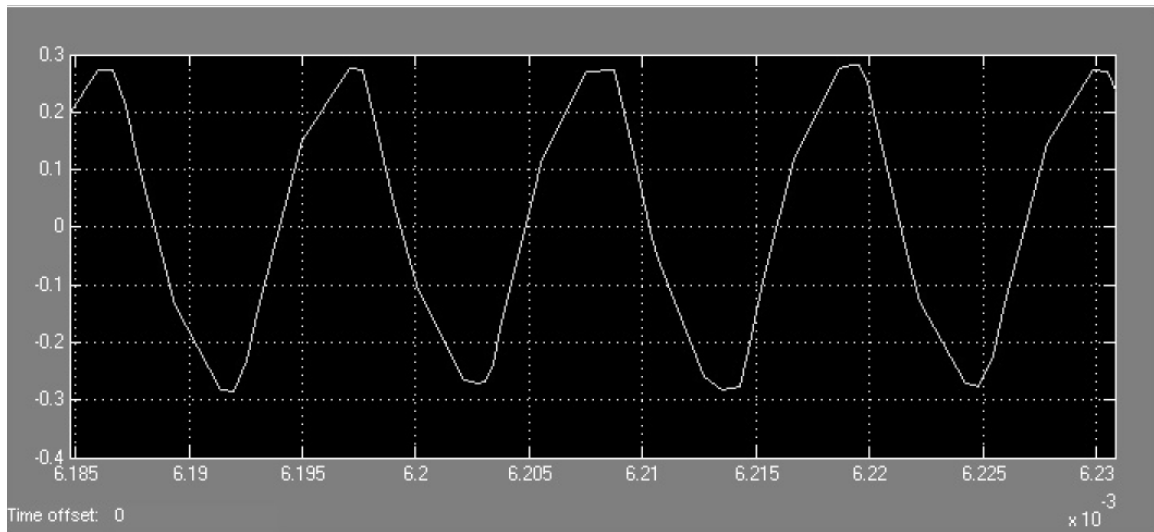


Figure 2.13 Fluorescent lamp current waveform in 91 kHz.

2.6 Summary

In this chapter, the components of a fluorescent light system are introduced, and in the following their principle of operations are carried out. In the next chapter, the mathematical model and then the Matlab-Simulink models of these component are accomplished.

3. System simulation

3.1 Introduction

In this chapter simulation of fluorescent lamp, electronic ballast and light sensor are presented. Simulation of fluorescent lamp is started with obtaining the lamp mathematical model from experimental data, and then the Matlab - Simulink model of fluorescent lamp is presented. The electronic ballast is simulated based on its electronic circuit. The light sensor is simulated, and with connecting of lamp, electronic ballast and light sensor models together, the complete simulated model of fluorescent light system is developed. Complete simulated model will be used in chapter 4 to carry out the design of the controller.

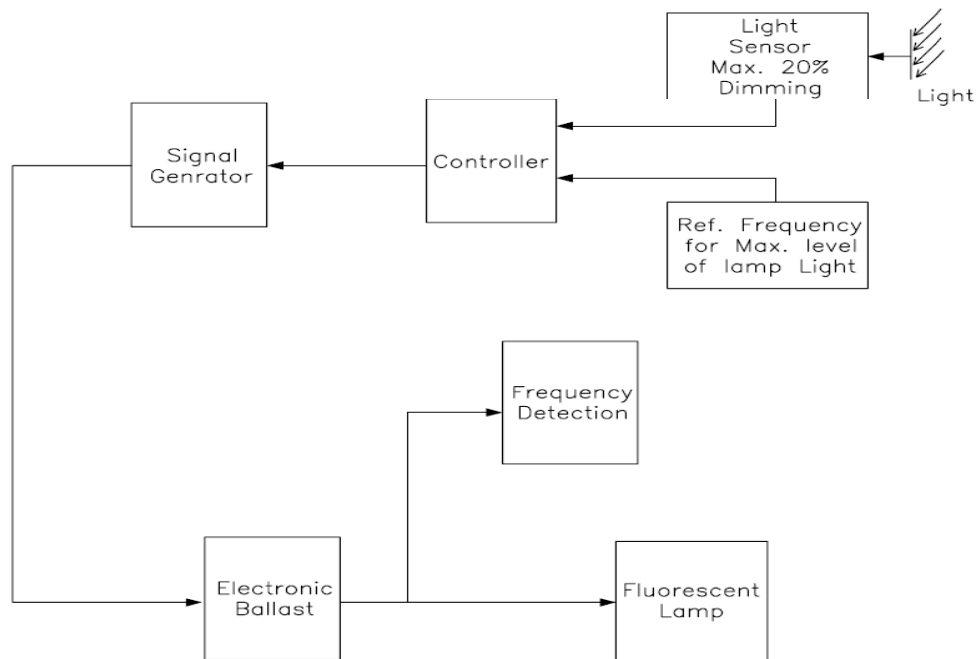



Figure 3.1 Block diagram of fluorescent light control system.

3.2 Fluorescent Lamp Simulation

As explained in chapter 2, the fluorescent lamp is connected to the main power supply via electronic ballast and the fluorescent lamp current is controlled by a switching sequence of the electronic ballast. In this section a Matlab - Simulink model of fluorescent lamp is developed to demonstrate this phenomena.

Table 3.1 shows that the current and voltage and the average power of the fluorescent lamp as the frequency is changed from 51 khz to 91 khz. It can be seen from this table that the current, voltage and average power of the fluorescent lamp decreases as the lamp frequency increases from 51 khz to 91 khz.

Table 3.1 V-I characteristic of a 32w General Electric fluorescent lamp.

Power Level	V _{RMS} [V]	I _{RMS} [AMP.]	P _{AVG} [W]	R _{lamp} [Ω]	Frequency [KHz]
maximum  minimum	99.5393	0.2888	28.2260	344.61	52.000
	103.1804	0.2576	26.0112	400.49	57.339
	104.6403	0.2321	23.8078	450.84	61.125
	110.9816	0.1974	21.4655	562.32	68.871
	113.2090	0.1821	20.1859	621.71	72.046
	114.1565	0.1690	18.8594	675.51	75.586
	120.2613	0.1424	16.7430	844.35	80.775
	126.6726	0.1134	14.0515	1117.2	85.000
	143.8952	0.0417	5.8999	3447.4	90.909

The resonance frequency of the series RLC circuit in electronic ballast is calculated based on the equation $1 + \frac{C_p}{C_s} = \omega^2 LC_p$, where C_p and C_s are the

parallel and series capacitors, ω is the resonant frequency and the L is the inductance. Based on the values of C_P and C_S calculated in the next section the resonance frequency is approximately 48 kHz. Since the electronic ballast works properly over the frequency range of 51 kHz to 91 kHz the operating frequency range for simulation is from 51 kHz to 91 kHz.

It can also be seen from the Table 3.1 that there is a large percent decrease in the fluorescent lamp current as compared to the lamp voltage. Therefore, the fluorescent lamp resistance is less at lower frequencies and increases as the frequency is increased.

Fluorescent lamp current is obtained from the relationship between the fluorescent lamp average power and the lamp resistance by using of a decreasing monotonic double exponential function. The equation is:

$$R_{lamp} = ae^{-bP_{lamp}} + ce^{-dP_{lamp}} \quad (3-1)$$

where R_{lamp} is the fluorescent lamp resistance and P_{lamp} is the fluorescent lamp average power and a, b, c, d are the coefficients of the exponential equation. Equation 3-1 represents a curve fitting to the experimental data of fluorescent lamp resistance versus lamp average power. The Levenberg-Marquardt algorithm (LMA) or least squares curve fitting based on minimizing of the error squares is chosen for this curve fitting.

$$S(p) = \sum_{i=1}^m [y_i - f(t_i|p)]^2 \quad (3-2)$$

Where pairs (t_i, y_i) are the experimental datas for fluorescent lamp resistance and avarage power and $f(t_i | p)$ is the function that is used for fitting. Using the Levenberg-Marquardt algorithm (LMA), a Matlab program is developed to find the fluorescent lamp resistance as a function of lamp avarage power is given by

$$R_{lamp} = 8147 e^{-0.2113 P_{lamp}} + 1433 e^{-0.0535 P_{lamp}} \quad (3-3)$$

The data points of the fluorescent lamp average power versus the lamp resistance and the best fitted curve to this data as a solid curve are shown in Figure 3.2.

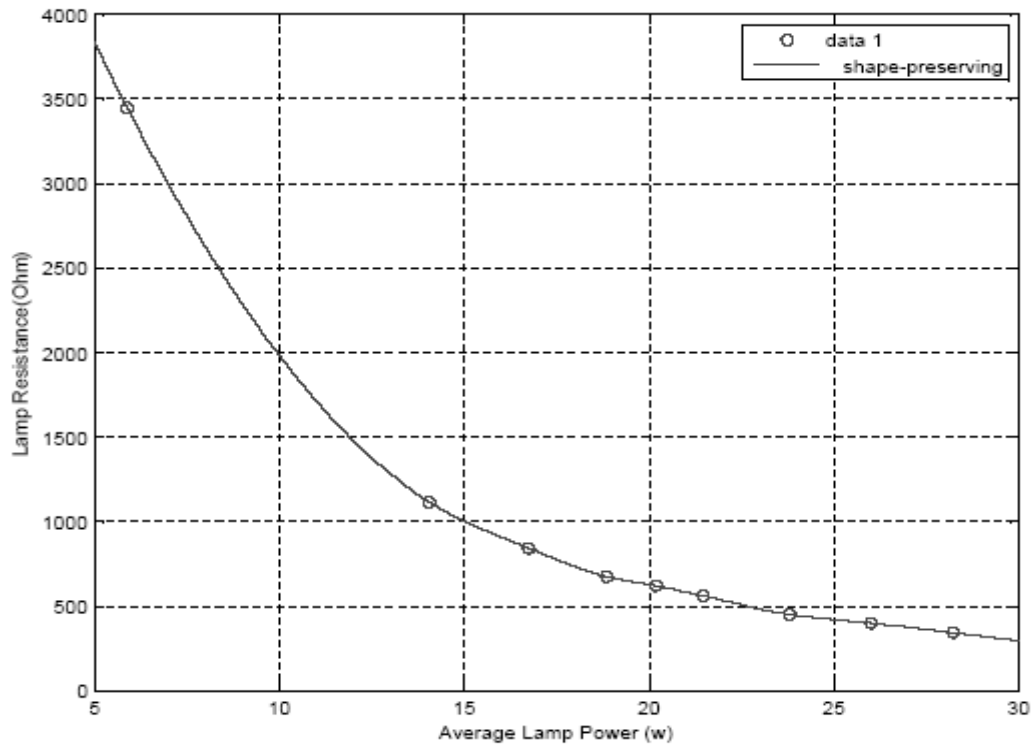


Figure 3.2 Curve fitting to the R-P characteristic of a 32W General electric lamp.

For Matlab-Simulink model of the fluorescent lamp, lamp voltage and lamp current are required. The relation between fluorescent lamp resistance and lamp current and voltage is given by equation (3-4).

$$i_{Lamp}(t) = G_{Lamp}(t) v_{Lamp}(t) \quad (3-4)$$

where $i_{Lamp}(t)$ is lamp current, $G_{Lamp}(t)$ is lamp conductance and $v_{Lamp}(t)$ is lamp voltage. The Matlab- Simulink model for this equation is shown on the Figure 3.3.

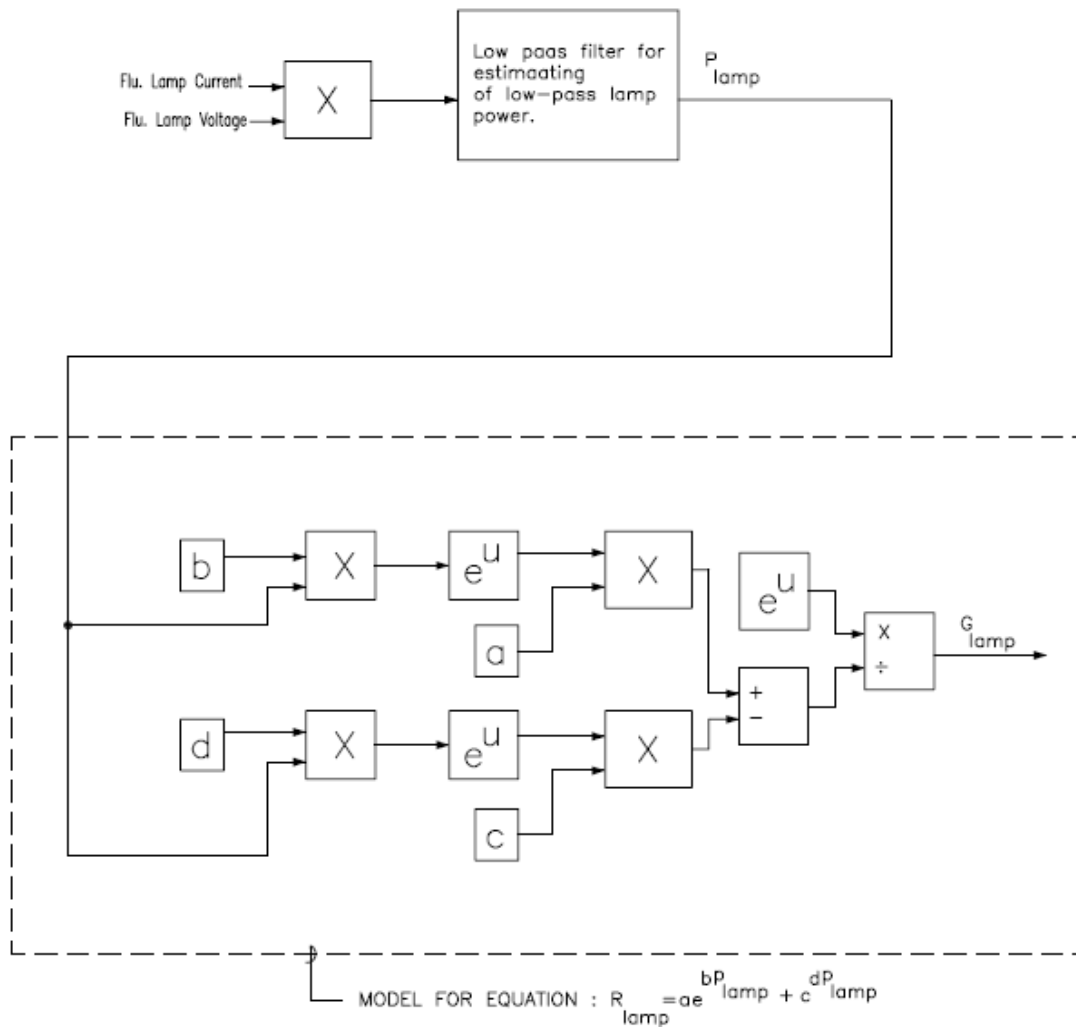


Figure 3.3 Matlab- Simulink model for fluorescent lamp.

Fluorescent lamp current and voltage are measured and multiplying of these values, lamp power is produced , The resulting instantaneous power is then filtered to estimate the low pass filtered lamp power. The time constant of the filter is related to ionization constant of the arc discharge and subsequently, equation (3-1) is implemented.

3-3 Electronic Ballast Simulation

Typical electronic ballast configuration is based on the half-bridge series-resonant circuit shown in Figure.2.10. In Figure 2.10, L is the inductance and C_S , C_P are capacitance and r_P is noise resistance for inductance of the ballast. If V_i is constant, and the quality factor on the load is sufficient high. (as explained on previous chapter), the current through the resonant circuit is sinusoidal and the current through the switches are half-wave sinusoidal and the voltage across the switches is a square wave. If the fluorescent lamp is off, it behaves as an open circuit, and it presents almost an infinite impedance. If the fluorescent lamp is on, its impedance presents finite value. With this information, the equivalent simplified circuit of the series resonant parallel-loaded ballast for the lamp off state can be shown in Figure 3.4.

This resonant circuit is a third-order low-pass filter that delivers power to the load mainly by the fundamental frequency. V_{s1} represents the rms value of the fundamental component. Based on the simplified circuit in figure 3-5, the output voltage V_{cp} is given by :

$$V_{CP} = \frac{V_{S1}}{j\omega L + \frac{1}{j\omega C_S} + \frac{1}{j\omega C_P}} \times \frac{1}{j\omega C_P} \quad (3-5)$$

and also

$$\frac{V_{S1}}{V_{CP}} = \left| 1 + \frac{C_P}{C_S} - \omega^2 LC_P \right| \quad (3-6)$$

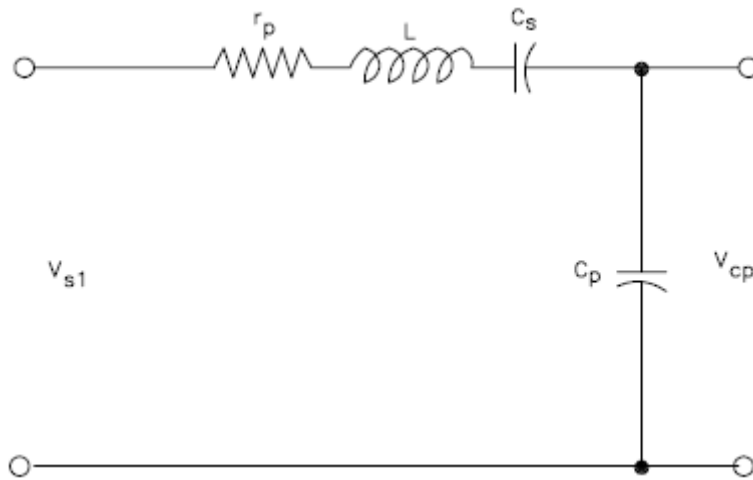


Figure 3.4 Equivalent simplified circuit of the series resonant parallel loaded ballast.

The maximum value of V_{cp} occurs when $1 + \frac{C_p}{C_s} = \omega_0^2 LC_p$ where ω_0 is the resonant frequency and giving $\omega_0^2 = \frac{1}{LC_p} (1 + \frac{C_p}{C_s})$. In a typical electronic ballast, a value for $A = C_P / C_S$ between 0.1-0.25 would normally be adequate for most ballast applications. For $f_0 = 46 \text{ kHz}$, $L = 0.0024 \text{ H}$ and $A = 0.1307$, the value of C_P is 1.6308×10^{-9} and hence $C_S = 1.4422 \times 10^{-9}$.

V_{s1} is the fundamental component of input DC voltage V_I and is given by $\frac{\sqrt{2}V_I}{\pi}$. An input value of $V_I = 400$ volt produces a value of $V_{s1} = 180$ volt which in turn produces the output value of $V_{Cp} = 143.8952$ volt. Since the fluorescent lamp does not present infinite impedance, a small corrective factor is applied to V_{Cp} . The equivalent simplified circuit of the series resonant parallel-loaded ballast for the minimum power is shown in Figure 3.5.

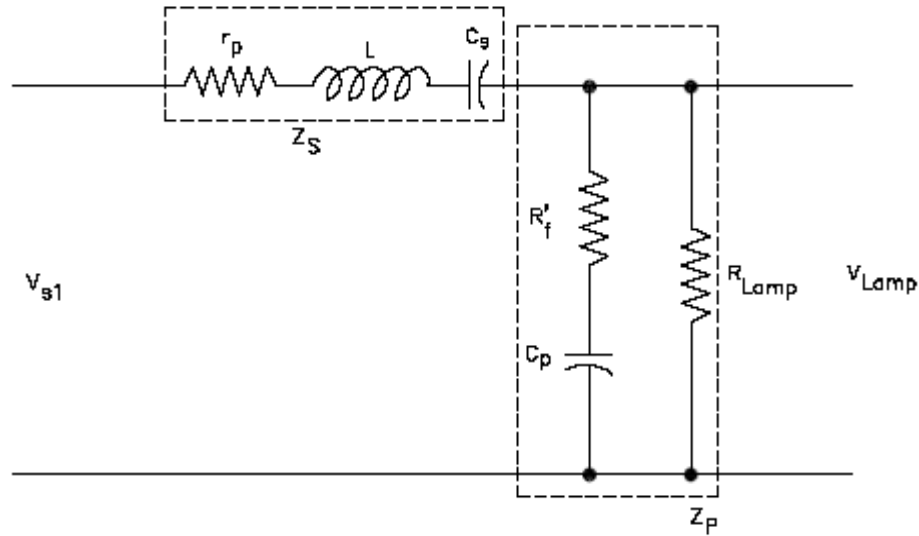


Figure 3.5 Equivalent simplified circuit of the series resonant parallel loaded ballast and fluorescent lamp.

From Figure 3.5, the voltage of the lamp can be written as

$$V_{Lamp} = \frac{V_{s1}}{Z_P + Z_S} \times Z_P \quad (3-7)$$

where

$$Z_p = \frac{1}{Y_p} = \frac{1}{\frac{1}{R_{Lamp}} + \frac{1}{R'_f + \frac{1}{j\omega C_p}}} \quad (3-8)$$

and,

$$Z_s = j\omega L + \frac{1}{j\omega C_s} + r_p \quad (3-9)$$

where r_p and r_{CP} are noise resistance for inductance and capacitance. With $V_{S1}=180\text{volt}$, $A=0.1307$, $L=0.0024\text{H}$, $C_p=1.6308 \times 10^{-9}$ and $C_s=1.4422 \times 10^{-9}$ and fluorescent lamp filament resistance $R'_f=9.6 \text{ ohm}$ (based on the manufacturer specification), the model of electronic ballast can be drawn as shown in Figure 3.6.

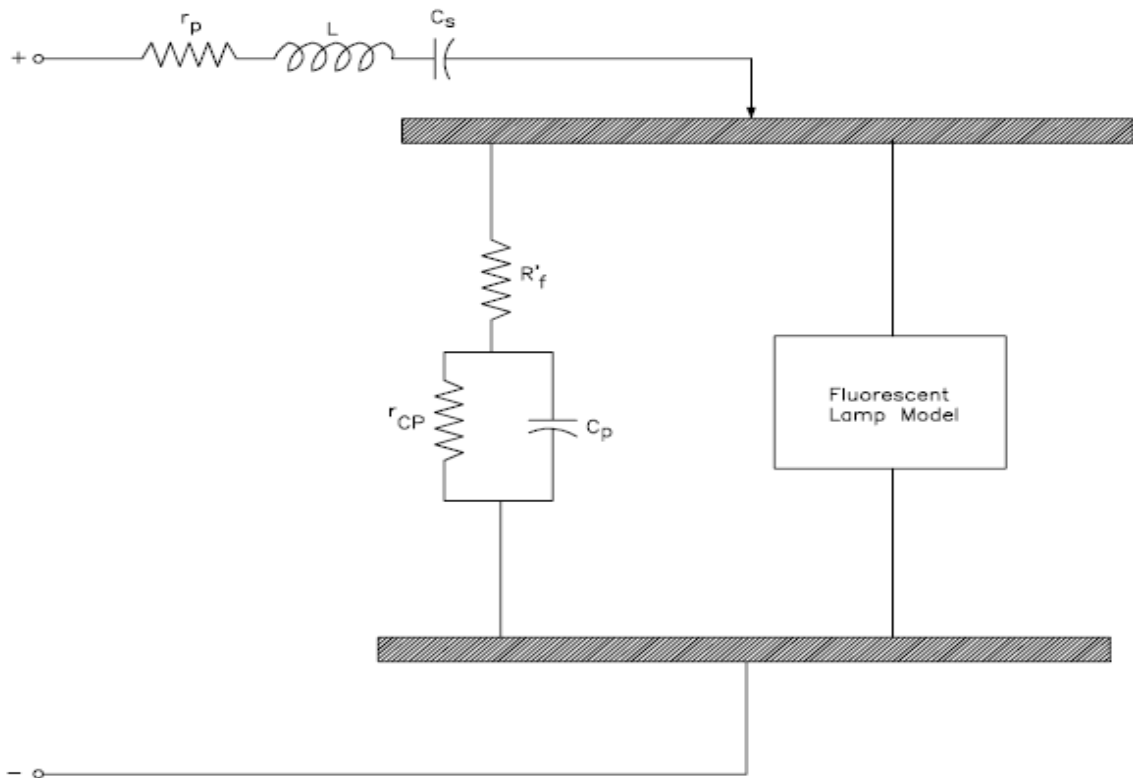


Figure 3.6 Matlab-Simulink model of electronic ballast with fluorescent lamp.

As explained earlier, the frequency of the input voltage applied to the electronic ballast is controlled by the frequency of the switching network. This is simulated in simulink by a controlled voltage source as shown in Figure 3.7.

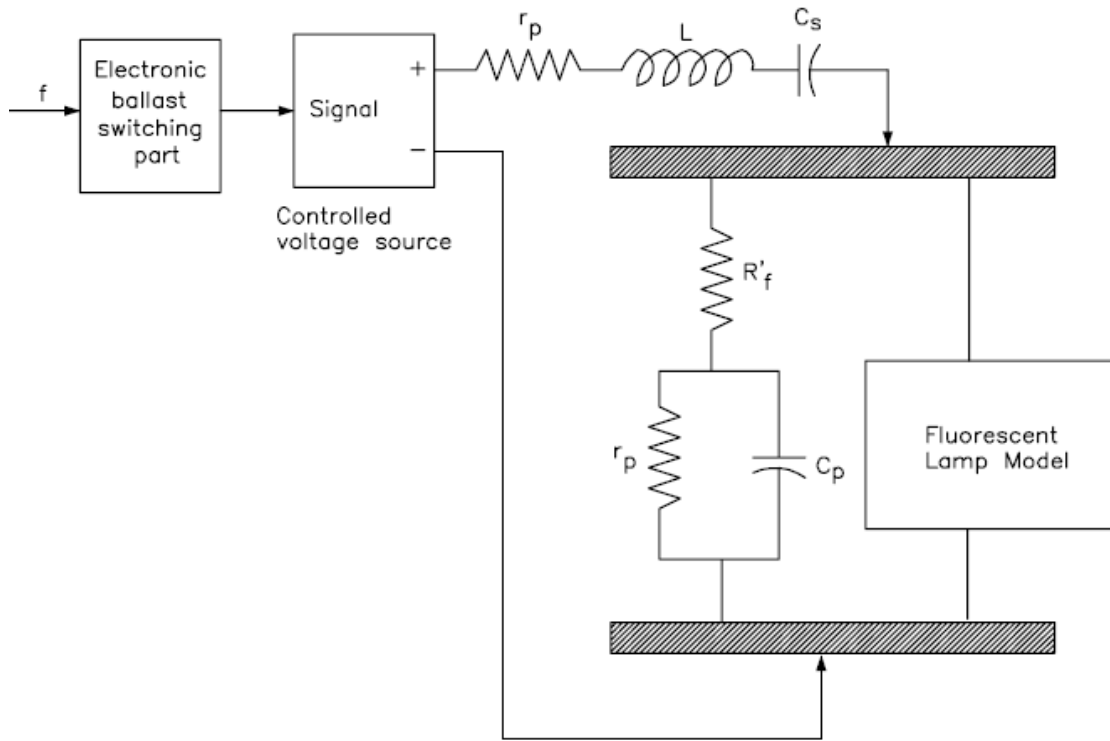


Figure 3.7 Matlab-Simulink model of electronic ballast with fluorescent lamp.

The fluorescent lamp in Figure 3.7 is now replaced by its simulin-matlab model developed in figure 3.3 and the complete model is shown in Figure 3.8.

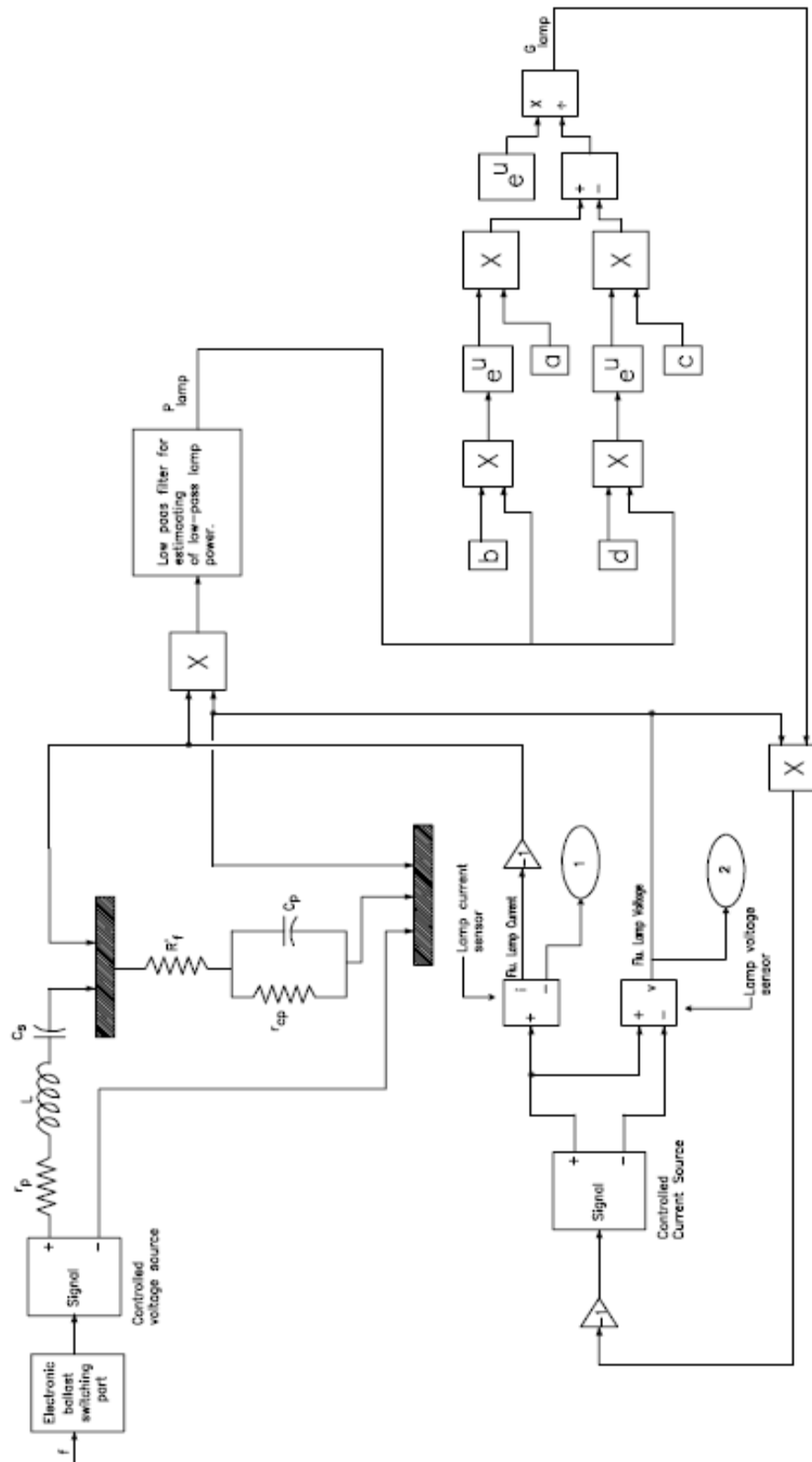


Figure 3.8 Complete Matlab-Simulink model of electronic ballast with fluorescent lamp.

3.4 Simulation results

Fluorescent lamp voltage and current obtained from the models are shown in Figures 3.9 and 3.10. it can be seen from the figures that the maximum voltage of the fluorescent lamp is about 150V (rms value of 102 volt)which compares to rms value of the voltage in Table 3.1.therefore, it is assumed that the Matlab simulation of the fluorescent lamp and electronic ballast implemented in Figure 3.8 is working properly in range of 52 khz to 91 khz and will be used for future design.

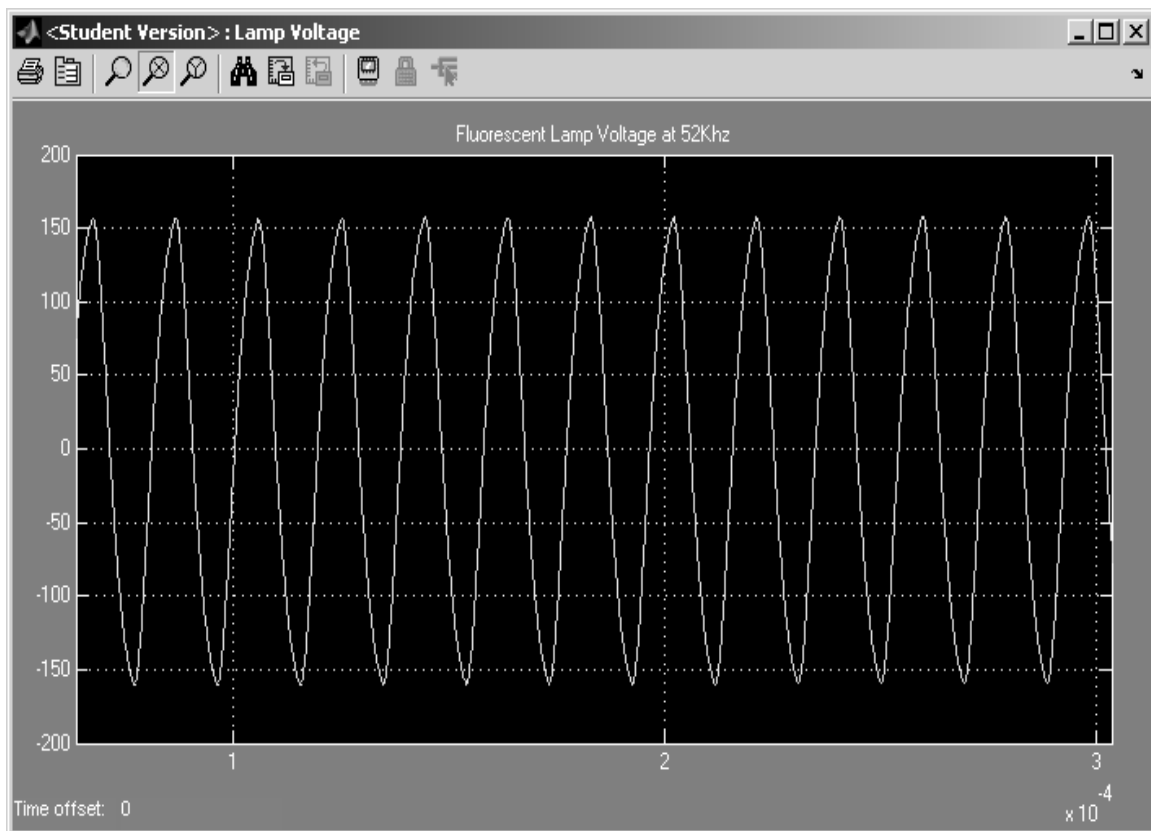


Figure 3.9 Fluorescent lamp voltage in 52 kHz.

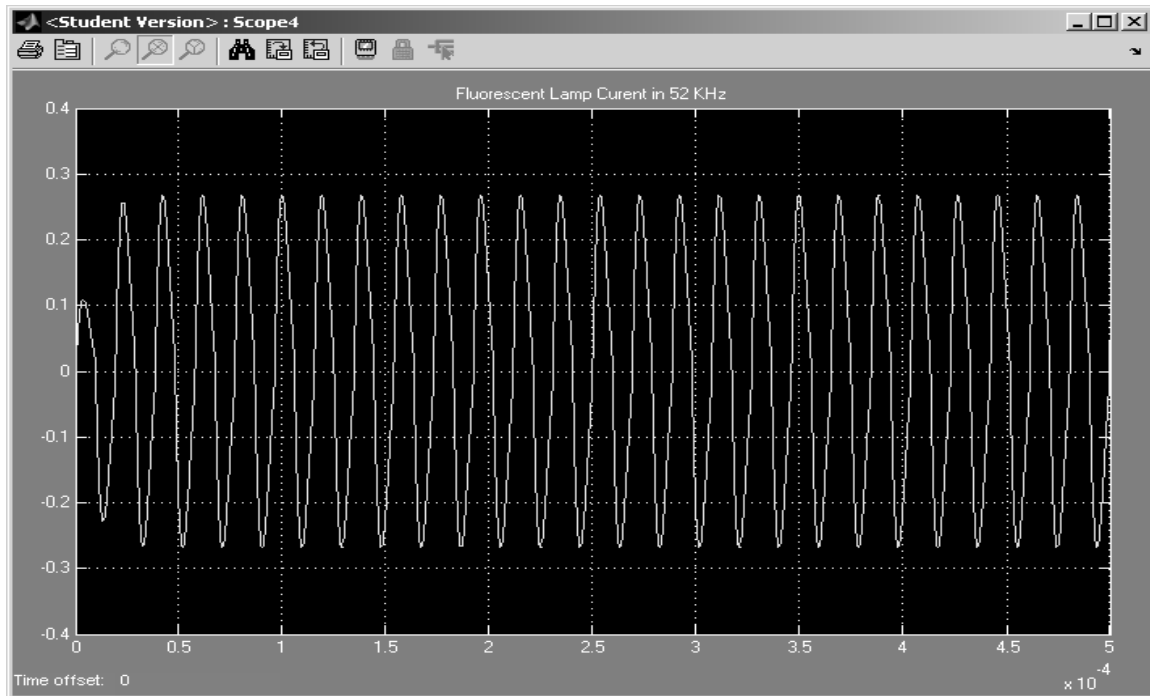


Figure 3.10 Fluorescent lamp current in 52 kHz.

Figures 3.11 and 3.12 show the fluorescent lamp voltage and current on 85 khz.

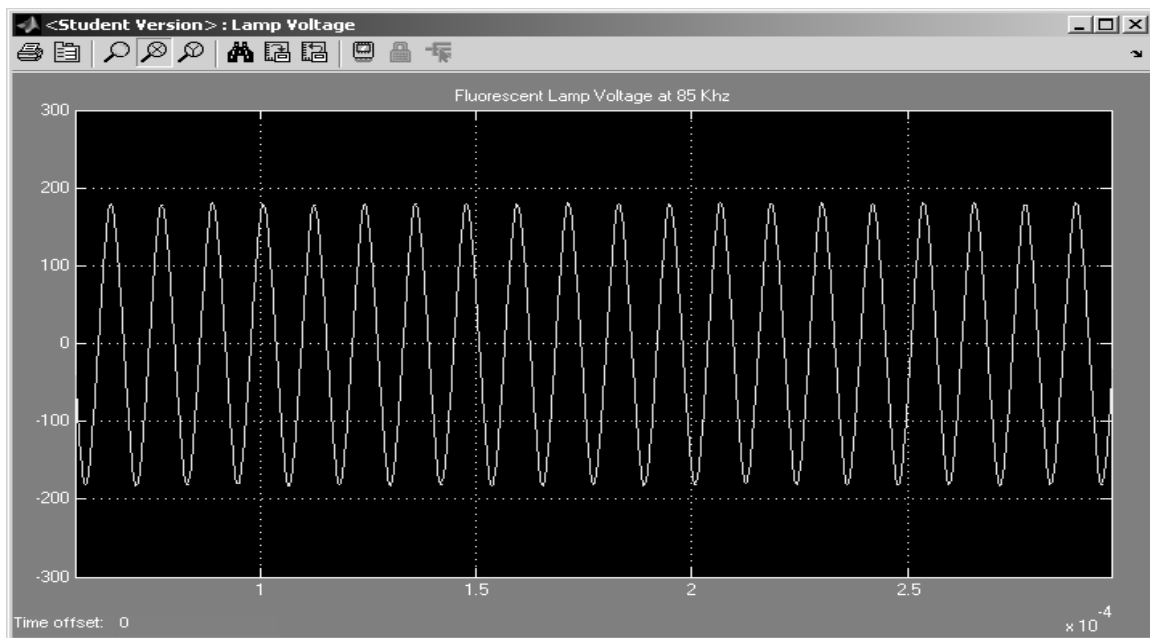


Figure 3.11 Fluorescent lamp voltage in 85 kHz.

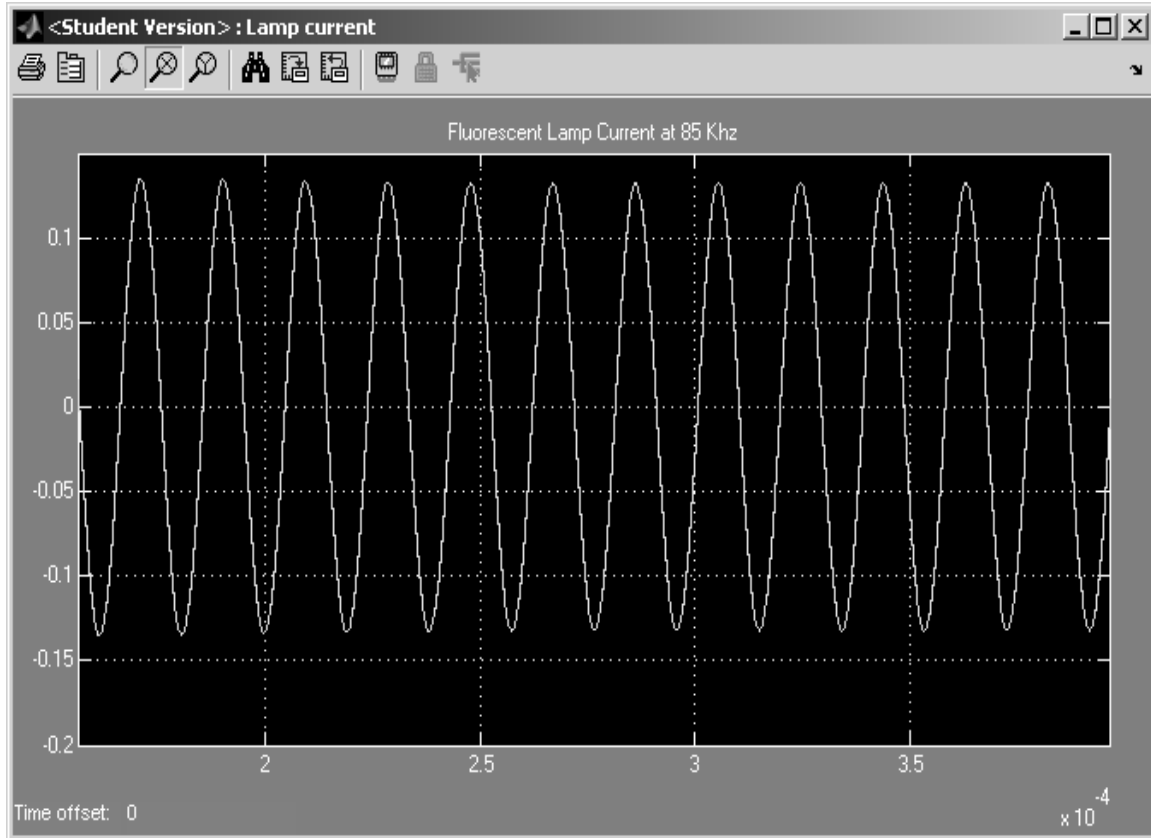


Figure 3.12 Fluorescent lamp current in 85 kHz.

3.5 Light Sensor Simulation

It was explained in chapter 2 that a light sensor is an LDR (light dependant resistor) whose resistance change with light as shown in Figure 3.13. It can be seen from Figure 3.13 that the behavior of the light sensor is not linear. A linear approximation in the range 51 kHz to 91 kHz is shown in Figure 3.14.

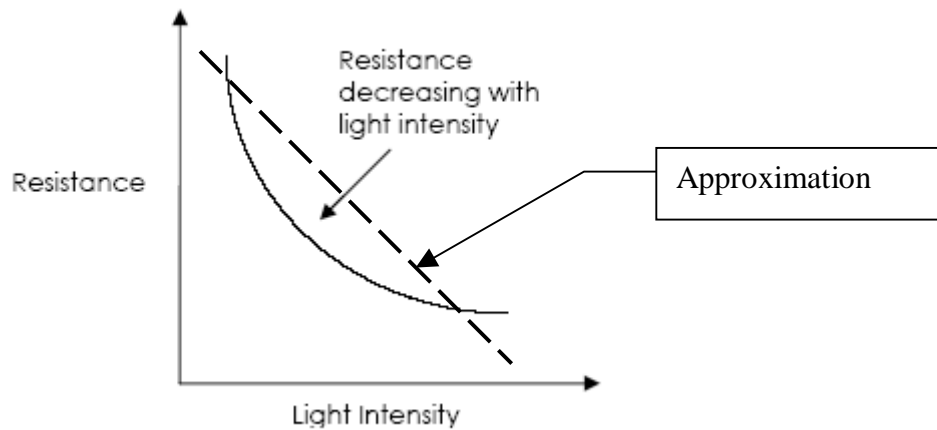


Figure 3.13 Resistance-Light characteristic of a light sensor.

Since the frequency range of the light is from 51 khz to 91 khz, 51 khz is compared to maximum light and 91 khz with minimum light, the range of light sensor should be 0 to 40. In other word, the output of the light sensor , V_{out} , should be 0 volt to 40 volt when the maximum light is entered the office. Figure 3.14 shows the light sensor circuit..

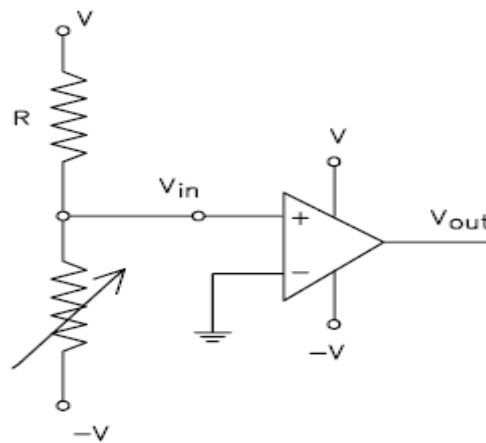


Figure 3.14 Light sensor circuit.

Light sensor circuit is a voltage divider circuit and with a proper values for R and V , V_{out} can be in the dimming range. V_{out} changes from 0 to 40 volt and as a number it is the frequency contribution of the light entering the office from

the window. Hence, for the light control system, the light sensor is considered gain block in the simulation.

3.6 Frequency Detection

As shown in Figure 3.1, the frequency of fluorescent lamp current is detected by a block named frequency detection block. The principal of the frequency detection is based on counting the zero crossing point of the fluorescent lamp current waveform. For every zero crossing of the fluorescent lamp, the current waveform subsystem is enabled and the time between two adjacent zero crossing is measured. The time between the zero crossing is used to find the frequency of the waveform as shown in Figure 3.16.

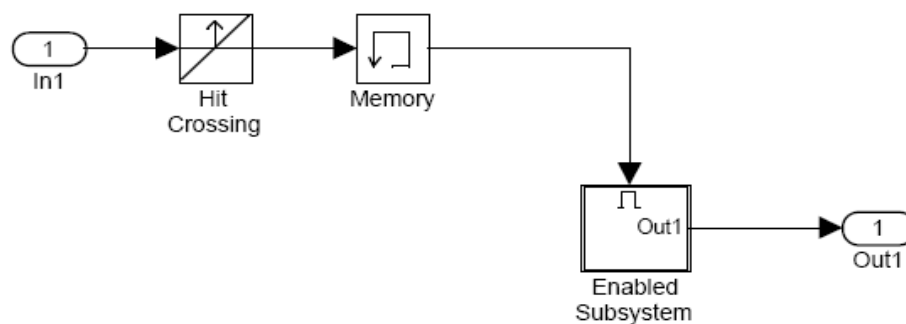


Figure 3.15 Frequency Detection Model.

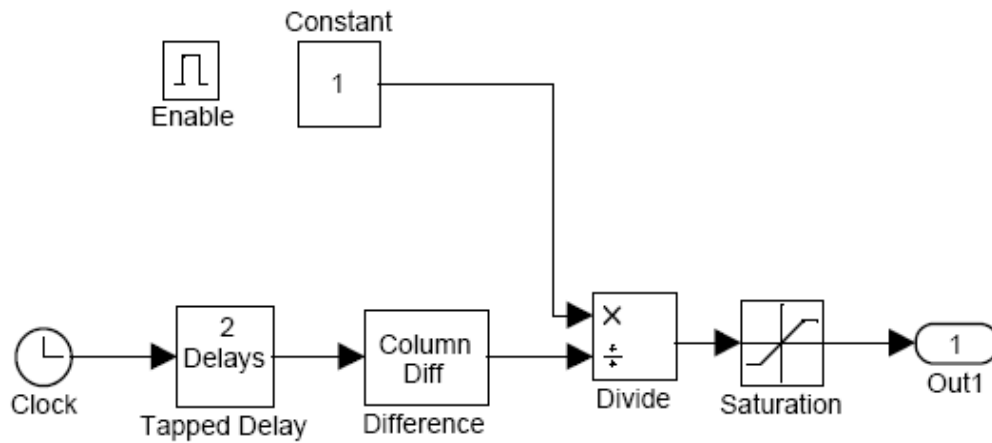


Figure 3.16 Frequency detection subsystem for measuring the frequency.

3.7 Signal generator Subsystem

The output of the light sensor is a number proportional to the outside light level entering the office as a frequency. The frequency from light sensor plus maximum light frequency of fluorescent lamp is the proper frequency for fluorescent lamp operation. A Matlab-Simulink subsystem is developed to generate the square waveform with this frequency for the electronic ballast. The subsystem is shown in the Figure 3.17. The completed Matlab-Simulink model of the system is shown in Figures 3.18 and 3.19.

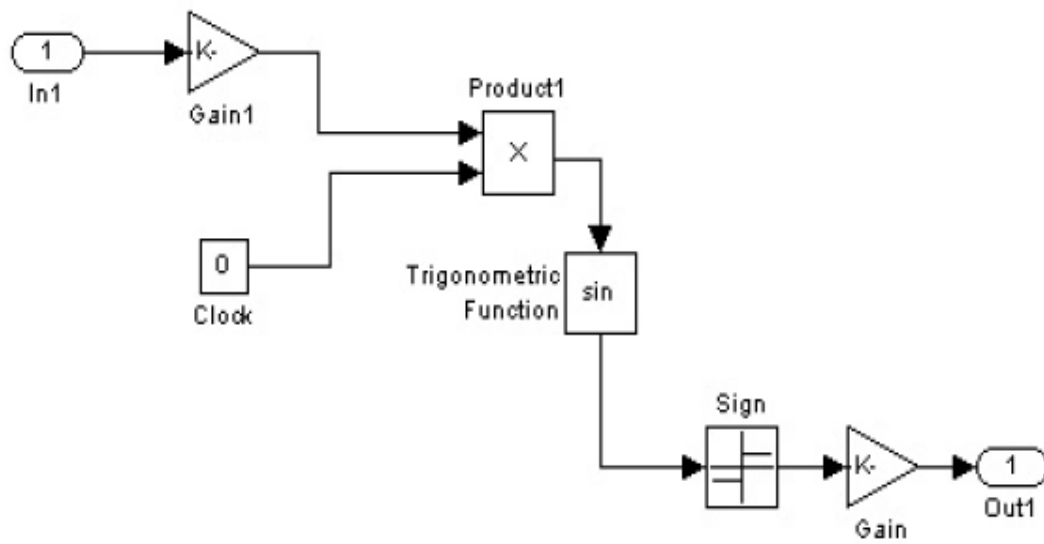


Figure 3.17 Signal generating subsystem.

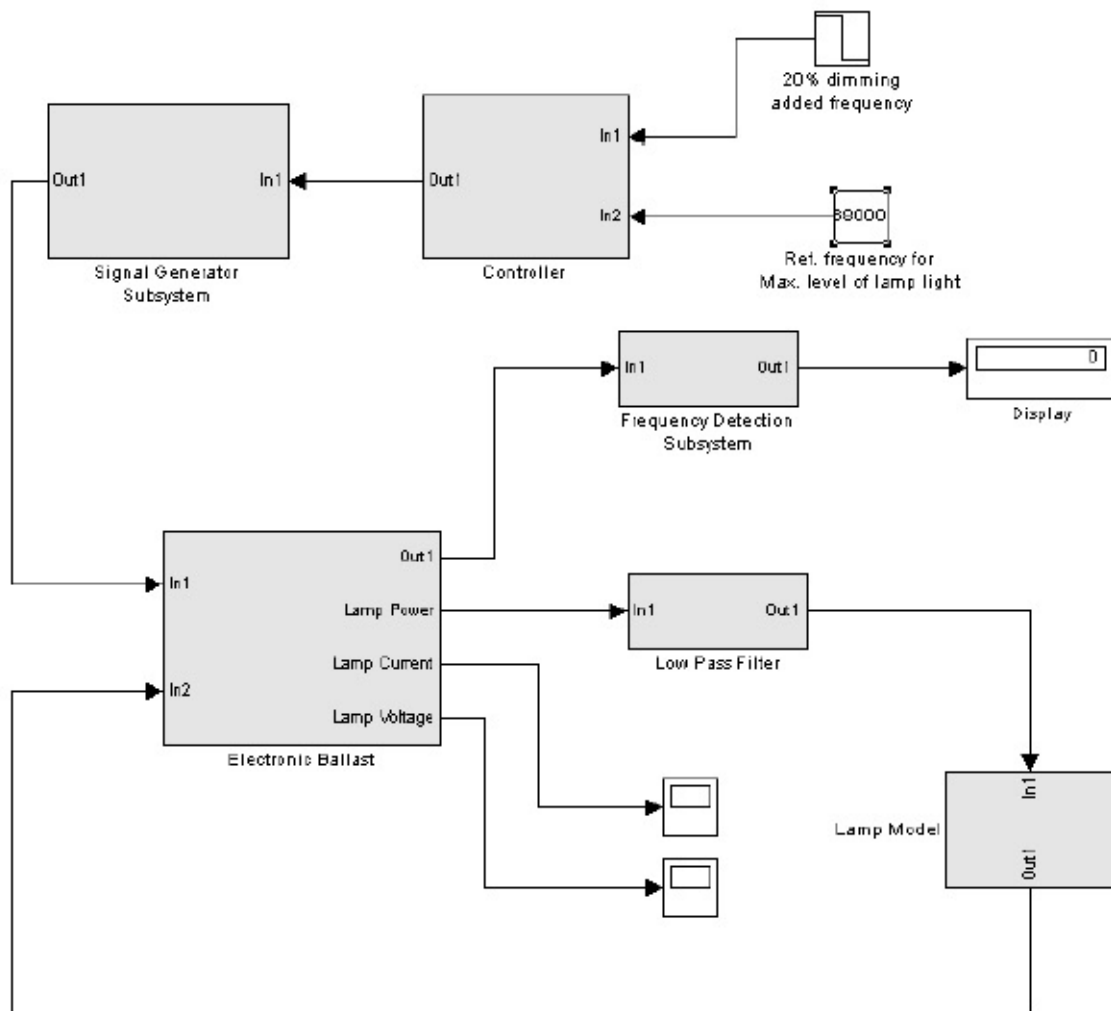


Figure 3.18 Complete block diagram model of light control system in Matlab-Simulink.

3.8 Summary

In this chapter a simulink model for fluorescent lamp, electronic ballast and light sensor are developed. This simulation is used in chapter 4 to design a fuzzy logic controller for the light control system.

4. Fuzzy Logic Controller

In this chapter, a step-by-step design of a fuzzy logic controller (FLC) for the fluorescent lamp light control is carried out. To understand the design process, the basic ideas of fuzzy set are necessary. A brief introduction to fuzzy logic is presented in section 4.1.

4.1 Introduction To Fuzzy Logic

4.1.1 Fuzzy Logic Theory

Fuzzy set theory is a mathematical concept proposed by Prof. Lotfi Asker Zadeh in 1965. This concept helps to improve the relationship between human and computers. Fuzzy logic is a kind of logic using graded or quantified statements rather than the ones that are strictly true or false. For example, today is *sunny*, might be 100% true if there are no cloud, 80% true if there is a few of cloud, 50% true if it is cloudy and finally, 0% true if it is raining all day. The results of fuzzy reasoning are not definite as those derived by strict logic. The fuzzy sets allow objects to have grades of membership from 0 to 1. These sets are represented by linguistic variables, which are ordinary language terms. The linguistic variables are used to represent a particular fuzzy set in a given problem, such as “large”, “medium” and “small”.

4.1.2 Fuzzy Set Definition

A fuzzy set in a universe of discourse is characterized by a membership function that takes the values in the interval $[0,1]$. Therefore a fuzzy set is a generalization of a classical set by allowing the membership function to take any value between 0 and 1. In other words, the membership function of a fuzzy set is a continuous function with range of $[0,1]$ or a fuzzy set is simply a set with a continuous membership function. A membership value of 1 means that an element is completely in the set whereas a membership value of 0 indicates an element is not in the set and the value between 0 and 1 means partial membership in the set. There are several types of membership function shapes: bell shaped, trapezoidal, gaussian, triangular etc. In this thesis, the triangular membership function is used because of its effectiveness and simplicity as shown in Figure 4.1.

A fuzzy set F in a universe of discourse U is characterized by a membership function μ_F , which takes values in the interval $[0,1]$, a fuzzy set F in U may be represented as a set of ordered pairs of a generic element u and its grade of membership function as

$$F = \{(u, \mu_F(u)) \mid u \in U\}$$

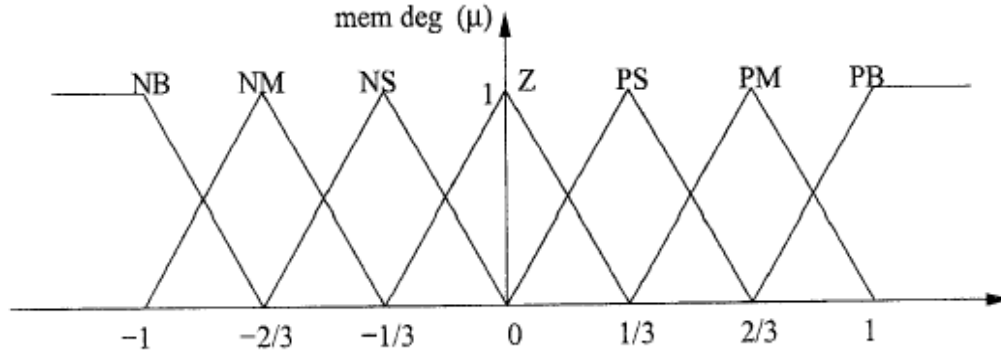


Figure 4.1 A typical membership set.

4.1.3 Fuzzy Set Theoretic Operations

Fuzzy sets have the same operations, which can be applied to crisp sets. Let A and B are two fuzzy sets in U with membership function μ_A and μ_B , respectively. The set theory operation of union, intersection, complement and other relations of fuzzy sets are defined by their membership function as:

1. Union: The membership function $\mu_{A \cup B}$ of the union $A \cup B$ is point wise defined for all $u \in U$ by

$$\mu_{A \cup B}(u) = \max\{\mu_A(u), \mu_B(u)\} \quad (4.1)$$

2. Intersection: The membership function $\mu_{A \cap B}$ of the Intersection $A \cap B$ is point wise defined for all $u \in U$ by

$$\mu_{A \cap B}(u) = \min\{\mu_A(u), \mu_B(u)\} \quad (4.2)$$

3. Complement: The membership function of the Complement of a fuzzy set A is point wise defined for all $u \in U$ by

$$\mu_{\bar{A}}(u) = 1 - \mu_A(u) \quad (4.3)$$

4. Cartesian Product: If A_1, \dots, A_n are fuzzy sets in U_1, \dots, U_n , respectively, the Cartesian product of A_1, \dots, A_n is a fuzzy set in the product space $U_1 \times \dots \times U_n$ with the membership function.

$$\mu_{A_1 \times \dots \times A_n}(u_1, u_2, \dots, u_n) = \min\{\mu_{A_1}(u_1), \dots, \mu_{A_n}(u_n)\}$$

$$\text{Or} \quad (4.4)$$

$$\mu_{A_1 \times \dots \times A_n}(u_1, u_2, \dots, u_n) = \mu_{A_1}(u_1) \cdot \mu_{A_2}(u_2) \dots \mu_{A_n}(u_n)$$

5 Fuzzy Relation: An n-ray fuzzy relation is a fuzzy set in $U_1 \times \dots \times U_n$ and is expressed as

$$R_{U_1 \times U_2 \times \dots \times U_n} = \{(u_1, \dots, u_n), \mu_R(u_1, \dots, u_n) \mid (u_1, \dots, u_n) \in U_1 \times \dots \times U_n\} \quad (4.5)$$

4.1.4 Linguistic Variables and Fuzzy Sets

Linguistic variables: A linguistic variable is characterized by a quintuple $(x, T(x), U)$ in which x is the name of variable. $T(x)$ is the term set of x , that the set of linguistic values of x with each value being a fuzzy number defined in U . For example, if Temperature is interpreted as a linguistic variable, then its term set

$T(\text{Temperature})$ could be

$$T(\text{Temperature}) = \{ \text{Cool, Warm, Hot} \}$$

Each term in $T(\text{Temperature})$ is characterized by a fuzzy set in the universe of discourse $U = [0, 40]$. “Cool” as “a temperature below about 10 deg”.

,"Warm" as "a temperature close to 20 deg." and "Hot" as "a temperature above 32 deg.". These terms can be characterized as fuzzy sets with their membership functions shown in Figure 4.2.

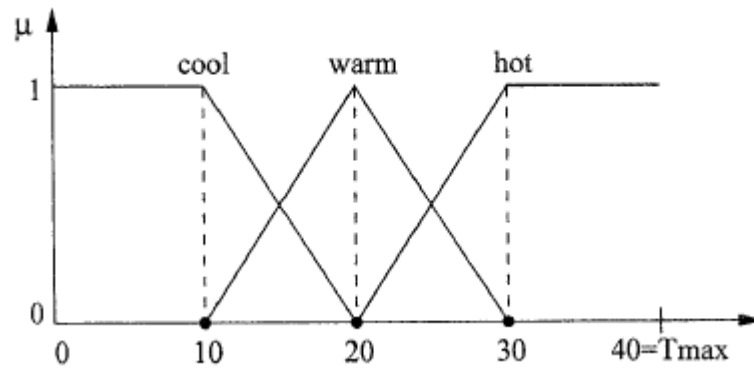


Figure 4.2 Fuzzy partition for the variable temperature.

Figure 4.2 also illustrates another important concept, that of a "fuzzy partition." In fuzzy partitioning, transition from one subspace into a neighboring one is smooth, that is, the membership degree of a point X in one subspace "warm" decrease as X gradually moves out of "warm" and move s into "hot". Figure 4.2 also shows that if the temperature is 15 degrees, then its membership vector would be $[0.5, 0.5, 0]$ and the sum of membership over the universe of discourse $[0, T_{\max}]$ is always equal to 1.

4.1.5 Fuzzy if-then rules

The point of fuzzy logic is to map an input space to an output space and the primary mechanism for doing this is the use of "if-then" statements called rules. Fuzzy rules are a series of "if-then" rules that are used to produce an output. All rules are evaluated in parallel, so the order of rules is not important. A

single fuzzy if-then rule assume the form: if x is A then y is B , where A and B are the linguistic values defined by fuzzy sets on the ranges X and Y .

The “if “ part of the rule “ x is A ” is called the antecedent and the “then” part of the rule “ y is B ” is called the consequent or conclusion. An example of such a rule might be “ if light level is high then frequency is high”. The antecedent of a rule can have multiple parts. The rule “ if x is A and y is B , then C is Z ” is a relation with two input variable in which case all membership degrees of the antecedent are calculated simultaneously and resolved to a single number using the logical operations described earlier in section 4.1.3. One way would simply be to make the degree match of the entire antecedent equal to the minimum of the membership degree or equal to the product of the first input variable membership value in x and the second input variable membership value in y .

4.1.6 Fuzzy Logic Controller

Fuzzy logic control design is somewhat different from conventional control design methods in that it departs from standard analysis tools such as the Bode plot (frequency response) and the root locus diagram. The advantages of the fuzzy control usually fall into the following categories:

- A fuzzy controller is more robust than a PID in a system where a traditional controller parameters change or the major external disturbances lead to sharp decrease in performance. In presence of such disturbances, PID controllers usually is faced with a trade-off between

reaction time and overshoot, they even run into problems in stabilizing the system at all.

- To develop a fuzzy controller is cheaper than developing a model-based or other controller. It is easier to understand and modify their rules.

Control engineers have successfully made use of fuzzy set theory in the design of controllers where uncertainty is present. Figure 4.3 shows the basic configuration of a FLC. It comprises of four principle components: a fuzzification interface, knowledge base, decision-making logic, and a defuzzification interface as shown in Figure 4.3.

1. The first component is the fuzzification interface that decomposes the system inputs into one or more fuzzy sets. The input values to the FLC also referred to, as the “crisp” values have to be converted to fuzzy values in order for the fuzzy controller to understand the inputs. This process is called fuzzification.
2. The knowledge base contains knowledge of the application domain and the related control signals. It consists of a “database” and a “linguistic (fuzzy) control rule base.” The database provides necessary definitions, which are used to define linguistics control rules and fuzzy data manipulation in a FLC.
3. The decision-making logic (inference) is the kernel of a FLC. It has the capability of simulating human decision-making based on fuzzy concepts and the rule of inference in fuzzy logic.

4. Defuzzification process is the reverse of fuzzification. The defuzzification interface (defuzzifier) converts the fuzzy set output values into a crisp value.

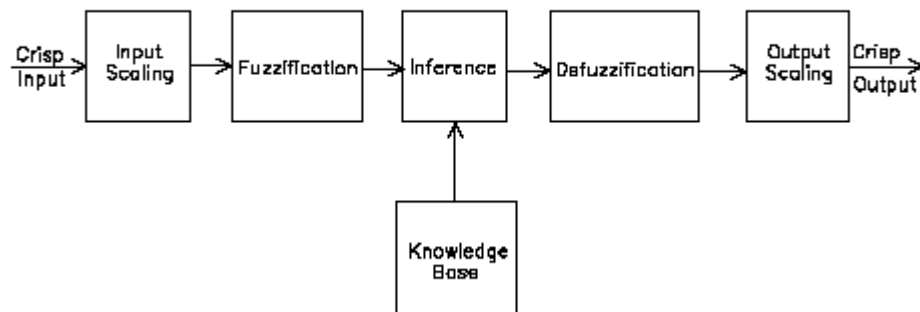


Figure 4.3 Configuration of a FLC.

4.1.7 Fuzzification

Fuzzification transforms a set of crisp inputs into a set of membership values in the corresponding fuzzy sets, and hence can be defined as a mapping from an observed input space to fuzzy sets in certain input universe of discourse. Each input domain is partitioned into several fuzzy sets, the number of which depends upon the precision of the process to be controlled. To do this, one must first construct a fuzzy partition that spans the input domain for each input variable. A fuzzy partition determines how many terms exist in a set and is equivalent to finding the number of primary fuzzy sets. For example in Figure 4.2, we have the sets as cool, warm and hot for the input variable temperature. The width of a fuzzy set extends to the peak value of each adjacent fuzzy set and vice versa as shown in Figure 4.4 and the peak value of a membership function

is a point where the function value is unity. Therefore, if all subset are implemented with the widths extended to adjacent peaks, the total membership over the universe of discourse for that variable will always be equal to unity. This is known as fuzzy partition.

Figure 4.4 shown that if the value of A is between A_j and A_{j+1} , then these two fuzzy subsets are active and the membership value μ_{A_j} and $\mu_{A_{j+1}}$ for the two fuzzy subsets within that region will depend on the point at which the input line cuts the two slopes. For any input value, the sum of all membership values over the universe of discourse is always equal to 1.

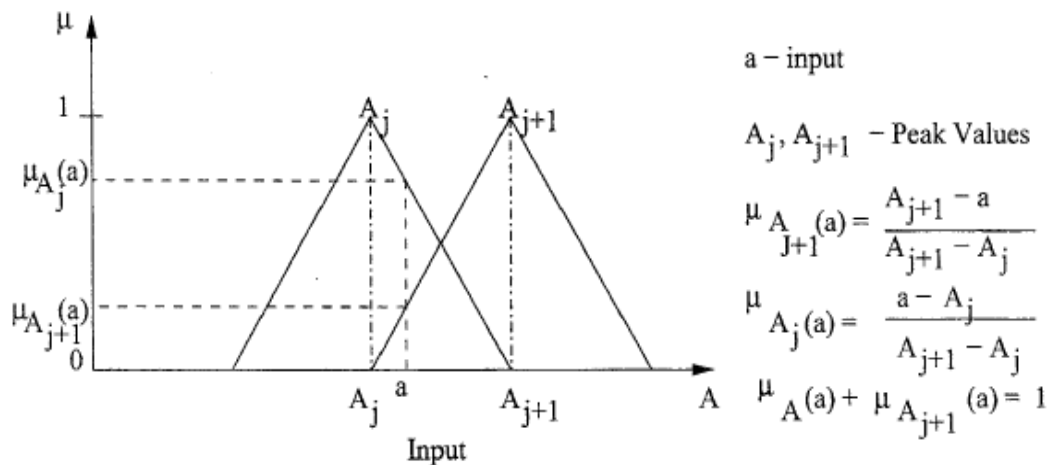


Figure 4.4 Two membership functions in the universe of discourse for the input variable.

4.1.8 Knowledge Base

The knowledge base of the fuzzy controller consists of a database of linguistics variables and fuzzy control (if-then) rules. A fuzzy rule base is simply a set of rules, described earlier, which state the relationship between the input

domain fuzzy sets and output domain fuzzy sets. For example, if we were designing a rule base for thermostat having temperature as input and computing the output fan speed, the rules might be:

If T is cool, then V is off

If T is warm, then V is low

If T is hot, then V is high

where the input domain is partitioned into three fuzzy sets “cool”, “warm” and “hot” and the output domain are partitioned into three fuzzy sets “off”, “low” and “high”. The rule base tells which fuzzy input sets affect a given fuzzy output set. A combination of inputs from different sources is used to derive the fuzzy control rules.

4.1.9 Inference

The process of fuzzy inference involves all of the pieces that are described in the previous sections: membership functions, fuzzy logic operators and if-then rules. The inference mechanism computes the truth-value for the premise of each rule, and applies the value to the conclusion part of each rule. The three commonly used inference methods are: min-max method, product-max method and product-sum method. In the min-max inference, the output membership function is clipped at a height corresponding to the minimum value between the membership degrees resulting from rules condition (fuzzy logic AND) as shown in Figure 4.5. in prod-max inference, the output membership function is scaled by the rule premise’s computed degree of truth as illustrated in Figure 4.6.

4.1.10 Defuzzification

The last step in the FLC is to use the degree of match of antecedents of the rule base along with the output fuzzy sets to convert the inferred fuzzy control action into a crisp one. The defuzzification process determines the crisp output by resolving the applicable rule into a signal output value.

The min-max inference method uses the min operator to resolve the strength of the rule's antecedent and the max to resolve the contribution of the rule. Figure 4.5 represents the case where two rules are activated involving 2 input variables (x & y) and one output variable (r). Assume that x be a measure of $x(t)$ at any time t and y be a measure of $y(t)$ at the same time. Consider the fuzzy sets with respective membership functions $\mu_{A1}(x)$, $\mu_{A2}(x)$, $\mu_{B0}(y)$ and $\mu_{B1}(y)$. Also assume the effected inference rule are:

If x is $A1$ and y is $B0$ then r is $C0$

If x is $A2$ and y is $B1$ then r is $C1$

The strength of the antecedents is realized by the minimum value between membership grades resulting from rule conditions (Figure 4.5: $\mu_{A2}(x)$ and $\mu_{B0}(y)$) and the membership functions of the respective output fuzzy sets (Figure 4.5 $\mu'_C(r)$ and $\mu'_{C0}(r)$). The implications (connective than) are realized by the clipping of the output sets and rules are finally combined by using the OR

operator and interpreted as the max operation for each possible value of the output variable. (μ_r on Figure 4.5) The final output is determined by a weighted average of all contributions of the output sets. The general form is:

$$u = \frac{\mu_{C0} + \mu_{C1}C2... + \mu_{Cn}C_n}{\mu_{C0} + \mu_{C1}.... + \mu_{Cn}} = \frac{\sum_{n=0}^{\#Outputsets} \mu_{Cn} C_n}{\sum_{n=0}^{\#Outputsets} \mu_{Cn}} \quad (4.6)$$

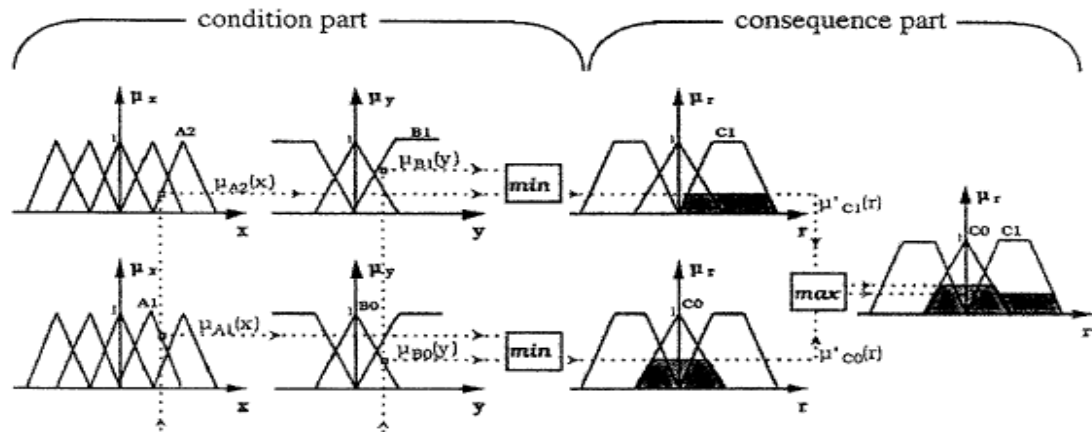


Figure 4.5 Min-max method form 2 rules involving 2 input 1 output variable.

The product-max method is similar to the min-max method except that all implication in the rules (then operation) is realized by a product instead of a minimum. The truth-values of the rule conditions are used to multiply uniformly the corresponding output sets instead of clipping them at a certain level as shown in Figure 4.6.

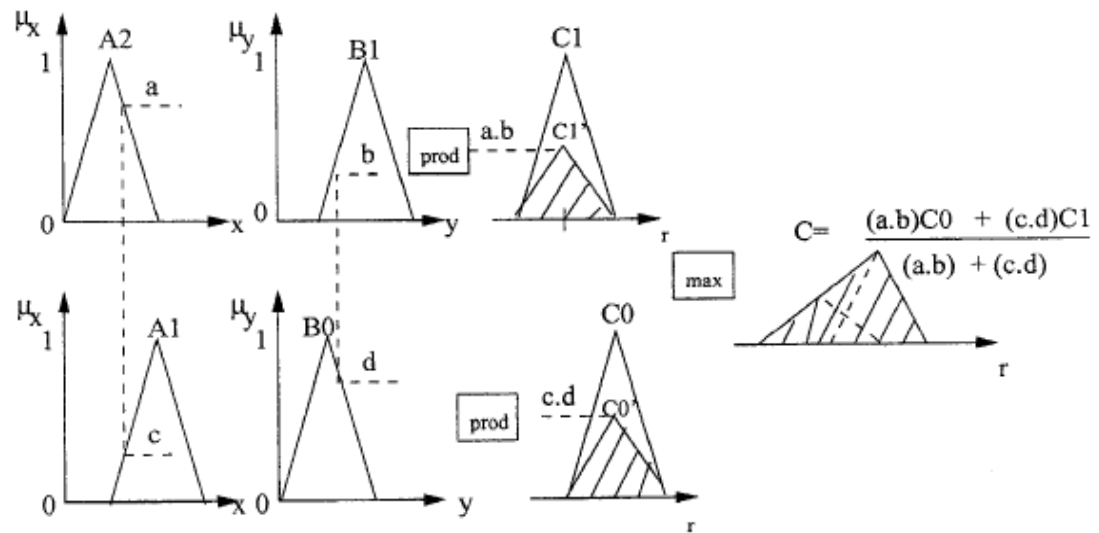


Figure 4.6 Prod-sum method for 2 rules involving 2 input and 1 output variable.

Another common method is the prod-sum method that uses the arithmetic mean and the product to realize respectively all the OR & AND operators. Unlike the MAX operator which select only the maximums values, the sum takes into account all involve sets and conserves part of the information that contain their shapes.

4.1.11 Fuzzy Control Based System

Let us consider a generic control problem. The block diagram of a feedback control system is shown in Figure 4.7. It shows a typical closed loop control consisting of input, a summer, a controller, a plant and the feedback loop. The purpose of the controller is to satisfy certain performance objective. For example, in case of controlling a disk at certain angle, the controller has to maintain the disk at some degrees according to the reference input. The summer subtracts the output of the plant from the input to determine how well the output

matches with the input to give the error signal. The controller corrects the error by supplying appropriate input to the plant. The input value to the controller is the error generated from the feedback loop, and the derivative of the error for a PD fuzzy controller. It can also have integral of the error for PI controller and all three (error, derivative of error and integral of error) for the PID fuzzy controller. All the three processes of fuzzification, inference and defuzzification are performed inside the fuzzy logic controller.

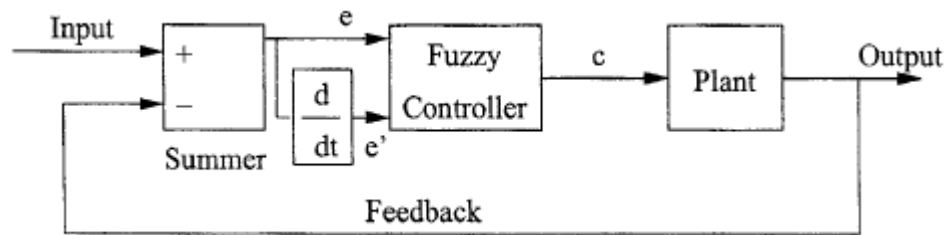


Figure 4.7 A closed loop control system.

Consider an FLC with 2-inputs error (e) and change of error (ce), and one output (c). Let us assume that there are 5 fuzzy sets (Negative Big (NB), Negative Small (NS), Zero (Z), Positive Big (PB) and Positive Small (PS) in the domain $[-1,1]$ with peak points at $[-1, -0.5, 0, 0.5, 1]$ for each input and output as shown in Figure 4.8. First the inputs are fuzzified and their membership in the fuzzy sets are determined. It can be seen from Figure 4.8, if input is $e=0.2$ and $ce=0.75$, then membership vector of e and ce would be

$$[0, 0, 0.6, 0.4, 1] \text{ and } [0, 0, 0, 0.5, 0.5].$$

Once fuzzification has been accomplished, the next step is to apply rule base and inference. The prod-sum method is used for inference. The rule base can be defined in the tabular form as shown in Table 4-1.

Table 4.1 5×5 Rule Base.

$ce \backslash e$	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

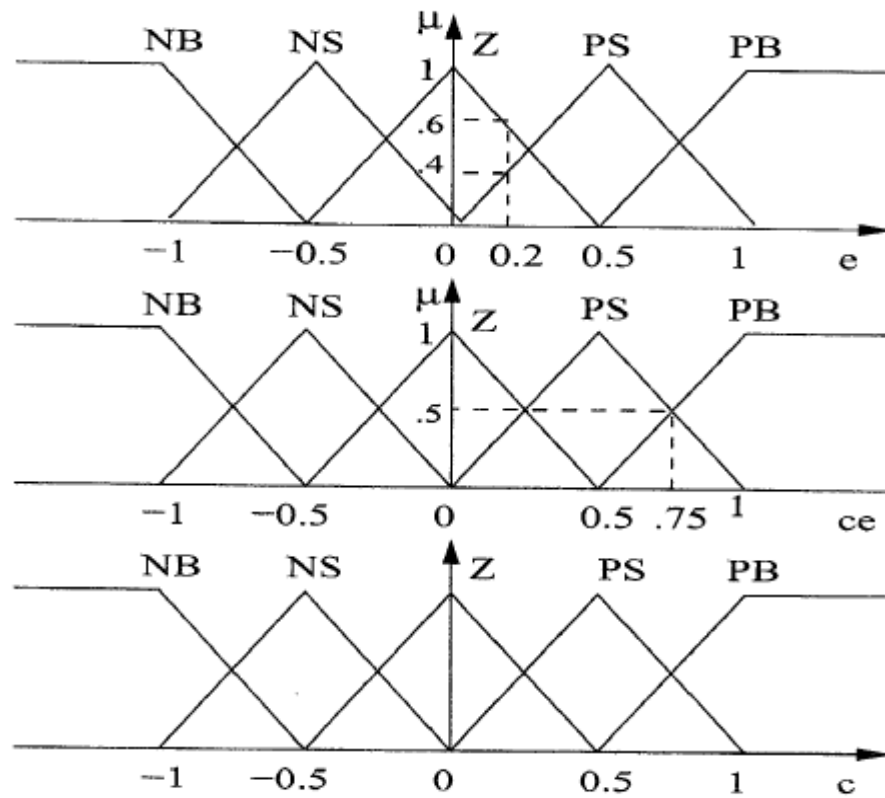


Figure 4.8 2-inputs, 1-outputs FLC.

The rule base table has 5 rows and 5 columns. So, we have total of 25 rules and only 4 rules will be active at any time. For the inputs $e=0.2$ and $ce=0.75$ four rules are active based on the two non-zero values of each input.

R1: if e is z (0.6) and c is e PS (0.5) then c is PS (0.5)

R2: if e is z (0.6) and c is e PB (0.5) then c is PB (0.5)

R3: if e is PS (0.4) and ce is PS (0.5) then c is PB (0.4)

R4: if e is PS (0.4) and ce is PB (0.5) then c is PB (0.4)

The last step in the process is defuzzification and the output ' c ' can be obtained (equation 4.6) by summing the product of center points from the rule base table with the product of the membership degree of the antecedents divided by the sum of products of the membership degree of antecedent. The output is calculated as

$$c = \frac{0.5 * 0.5 + 0.5 * 1 + 0.4 * 1 + 0.4 * 1}{0.5 + 0.5 + 0.4 + 0.4} \quad (4.6)$$

Fuzzy logic has emerged as a practical and successful alternative for controlling complex or undefined systems and uses a completely different approach than the traditional controller. This chapter showed that most fuzzy logic control systems are not based on a mathematical model of the system, but are based on the rule-base for controlling the systems where control rules are obtained from human operator's experience or engineer's knowledge of the system.

4.2 Controller design for the fluorescent lamp light system

4.2.1 Introduction

Proper amount of light in a business office is very important for health and productivity of the employees. The Illuminating Engineering Society of North America (IESNA) has specified minimum light level required for all kind of activity and task as shown in Table 4.2.

Table 4.2 Minimum light level required for buildings and activates (Illuminating Engineering Society of North America).

I. Illuminance Categories and Illuminance Values for Generic Types of Activities in Interiors				
Type of Activity	Illuminance Category	Ranges of Illuminances		Reference Work-Plane
		Lux	Footcandles	
Public spaces with dark surroundings	A	20-30-50	2-3-5	General lighting throughout spaces
Simple orientation for short temporary visits	B	50-75-100	5-7.5-10	
Working spaces where visual tasks are only occasionally performed	C	100-150-200	10-15-20	
Performance of visual tasks of high contrast or large size	D	200-300-500	20-30-50	Illuminance on task
Performance of visual tasks of medium contrast or small size	E	500-750-1000	50-75-100	
Performance of visual tasks of low contrast or very small size	F	1000-1500-2000	100-150-200	
Performance of visual tasks of low contrast and very small size over a prolonged period	G	2000-3000-5000	200-300-500	Illuminance on task, obtained by a combination of general and local (supplementary lighting)
Performance of very prolonged and exacting visual task	H	5000-7500-10000	500-750-1000	
Performance of very special visual tasks of extremely low contrast and small size	I	10000-15000-20000	1000-1500-2000	

Lighting design engineer calculate the number of light fixtures, lamp type and the light level based on the values in Table 4.2. The calculation of the light

level is based on the type of activities preformed in the office. No attention is generally paid to the outside light entering the office from windows.

On a sunny day, the sunlight coming into office may be more than enough to carry on the necessary task, Hence, there is a need of a control system to control the light level at a proper level as specified in Table 4.2 and save energy. For all figures, the time unit is second, current unit is ampere and voltage unit is volt in this chapter and also, the first part of the light control system response is related to the initial condition and is not part of the response.

4.2.2 Controller Design

Presently, the main source of light in most offices is from a regular 2'x4' fluorescent fixture containing three or four 32 watt lamps. On a sunny day, there may be enough sun light entering the office from a window or windows and hence it may be possible to save energy by dimming the fluorescent lamps. Dimming of the fluorescent lamp is possible by changing the frequency of the sinusoidal waveform as explained in chapter 3.

It was shown in chapter 3 that the maximum light for a 32-watt General Electric fluorescent lamp occurs at 51 kHz and the light is at a minimum level at 91 kHz. It is assumed that the light from the sun increases light level in the office by about 20%. In other word, it is possible to dim fluorescent lamp by 20%. (Dimming percent of light level depends on the office and window dimensions and can be calculated by a light meter during of a sunny day). Fluorescent lamp frequency changes from 51 khz to 91 khz therefore, for 20% of the light dimming,

frequency range for dimming is of 8 kHz. Thus,, the controller should increase or decrease fluorescent lamp frequency by a maximum value of 8 kHz.

The controller has two inputs; one input is from the light sensor, which is a number within the linear range of the light sensor as discussed in chapter 3 and, the other input is a number equivalent to the reference frequency at which fluorescent lamp has maximum light level. Maximum light level for the simulated lamp in this study is 51 kHz.

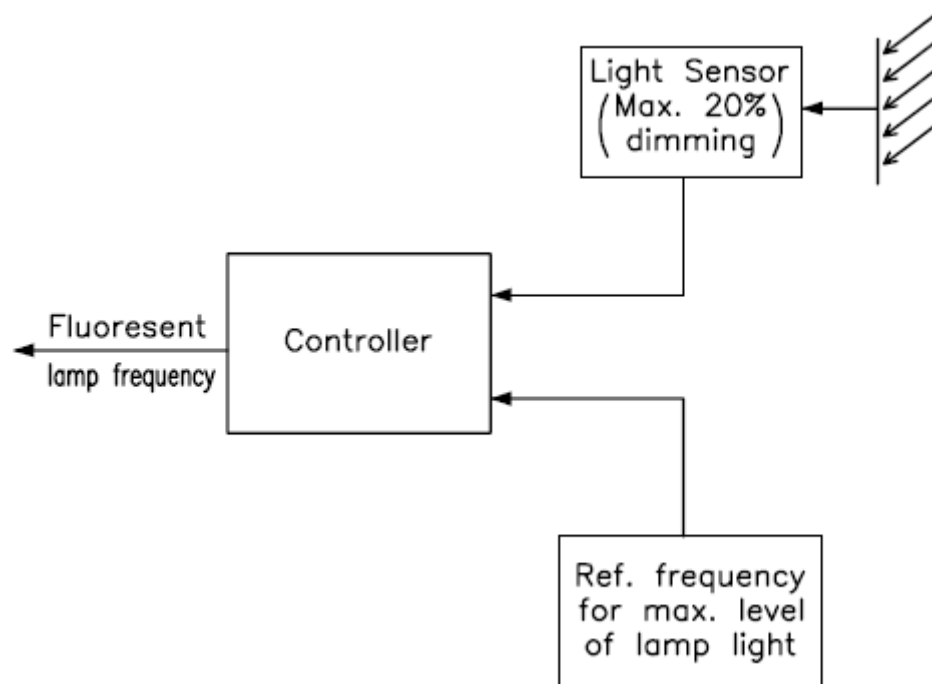


Figure 4.9 Controller for the fluorescent light control system and its inputs.

The light sensor is installed on the window frame so that it accepts light (or the majority of outside light) only from the outside. With any increase or decrease in the outside light, the outside portion of the frequency will be low or high, respectively and the fluorescent lamp will be dimmed accordingly. Figure 4.10 shows the block diagram of the controller.

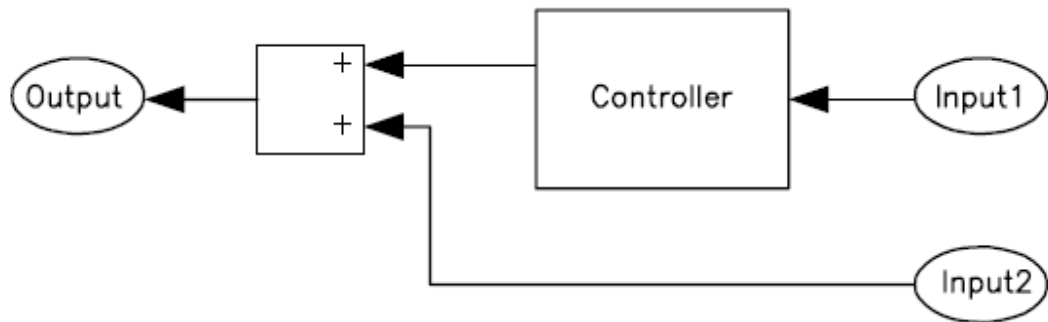


Figure 4.10 Block diagram of the controller.

The frequency of the fluorescent lamp is monitored as the output of the light control system. Increase in the outside light level causes more light in the office and thus increase the frequency of the input to the controller resulting in reduction of the light level from the fluorescent lamp. Often outside light is changed slowly and since a 20% change in light level causes a total change of 8 khz change in frequency, the fluorescent light control system is tested by applying an incremental change of 1khz. Figure 4.11 shows the response of the light control system to a change of 1 khz in frequency. It can be seen from figure 4.11 that a change of 1 kHz in the input frequency (a step function with a magnitude of 1 khz) produces an overshoot of 20 khz in the frequency of the fluorescent lamp. More overshoot produces more noise returning to the electronic ballast and rectifier circuit and brings low power factor. This is undesirable and therefore a controller is needed to reduce the overshoot. Since the outside light produces linear change in the output of the light sensor, a classic proportional controller can be used. However, this controller is not able to reduce overshoot because of the constant proportion gain requirement. The

other problem with classic proportional controller is that a large change in the outside light due to sudden change in the weather or due to closing of blind in the window would produce a large overshoot in the output resistance of the lamp and the reduction in light level will not be smooth. It is necessary that the light level be changed smoothly. Therefore, there is a need for a controller, which divide the large change in light level to small increments while changing the light level of the fluorescent lamp.

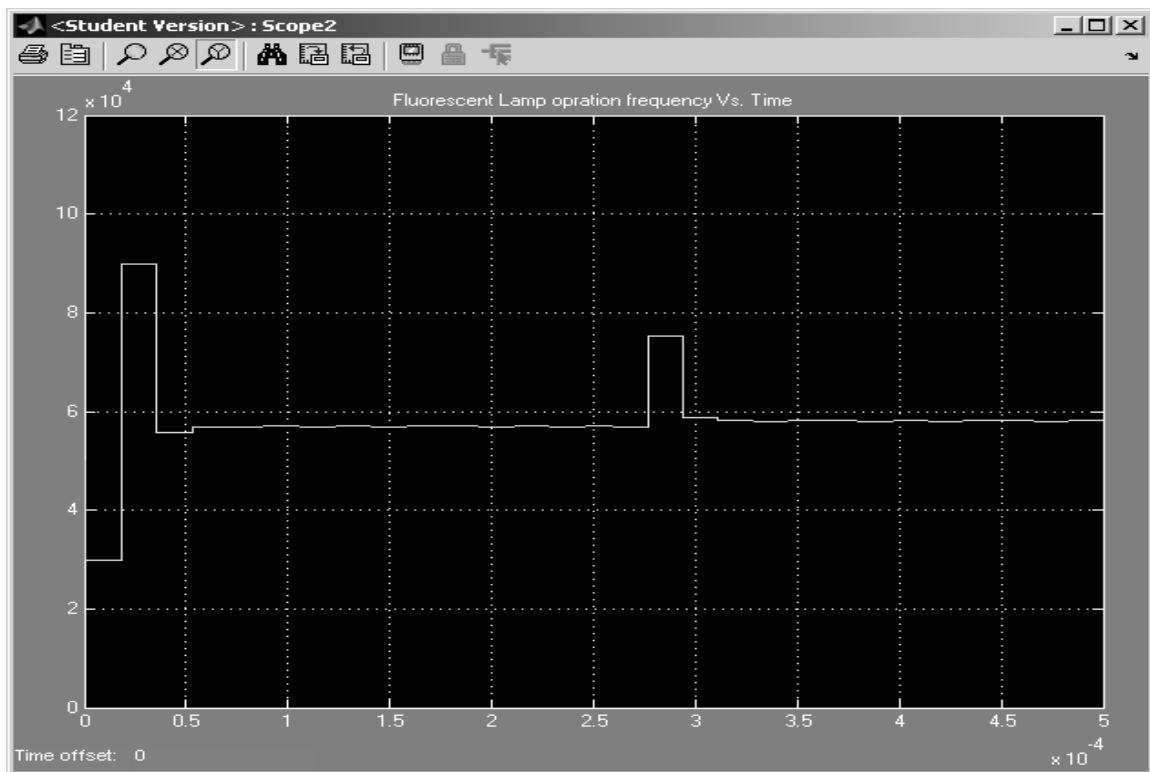


Figure 4.11 Light control system response to 1 KHz change in frequency.

A fuzzy logic controller (FLC) is able to divide a large change of the outside light to small increments resulting in small overshoot in the fluorescent

lamp overshoot. Simulink model of the fuzzy logic controller is shown in the figure 4.12.

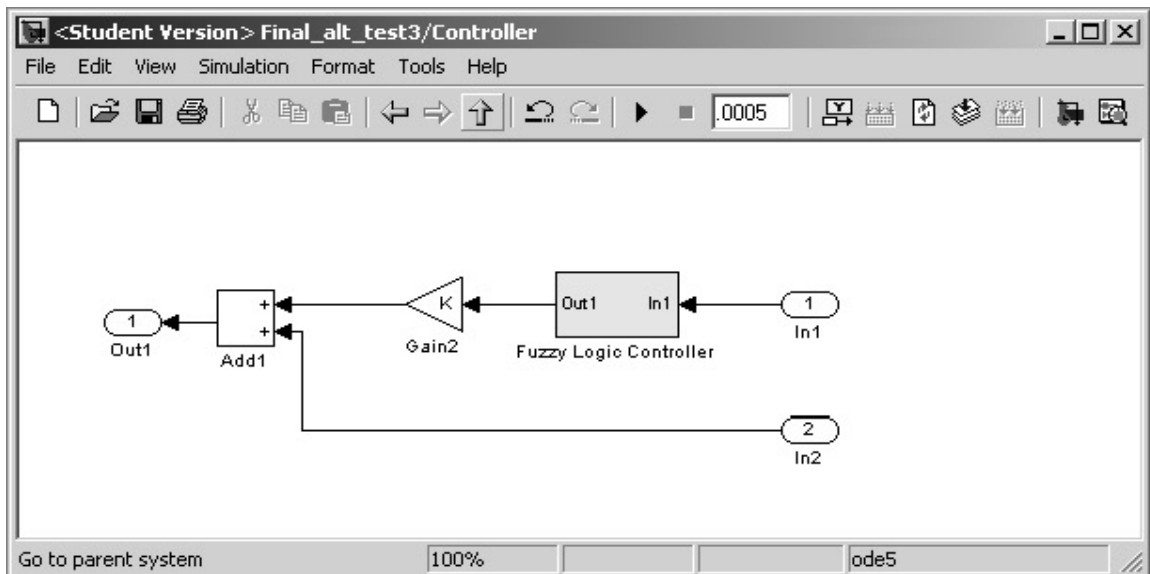


Figure 4.12 Simulink model of the fuzzy logic controller.

4.2.3 Fuzzy Logic Controller

The main problem with the classic controller is that it provides constant gain for all possible inputs to the system. For example, if the change in the input light from outside is small, it is desired that the change in the frequency and hence the light from the lamp be small. However, if the change in the outside light level is large, the resulting change from controller be large. It is not possible for the classical gain to provide different gains for different inputs. Hence, there is a need for a non-linear controller to control the light level of the fluorescent lamp. Fuzzy logic controller is one such controller whose control surface is piecewise linear. As explained earlier by choosing the center points of the input and output fuzzy set, we can select different gains for different inputs. Also, by increasing

the number of fuzzy sets, the gain can be increase smoothly. In this thesis, to test the ability of this approach, five fuzzy sets are selected for both input and outputs. The rule-base for the proportional fuzzy controller gives the following if then rules.

If input is zero then output is zero

If input is positive small then output is positive small

If input is positive medium then output is positive medium

If input is positive Big then output is positive big

If input is positive Large then output is positive large

The Input and output scaling is carried out based on the full range of fluorescent lamp dimming. As explained earlier, for the 20% dimming of light level, the total change in frequency for input is 8 kHz. In other word, the input domain is $[0 \ 8]$. The fluorescent lamp light level should change smoothly because a big change in the fluorescent light level is not desired for somebody who works in the office. Since 40 khz is the total range of fluorescent lamp light and $1/40$ time of full range light is selected for the output domain in this thesis. Therefore, the output domain is $[0 \ 1]$. Using equally spaced five fuzzy set for inputs and outputs, the fuzzy set are given by :

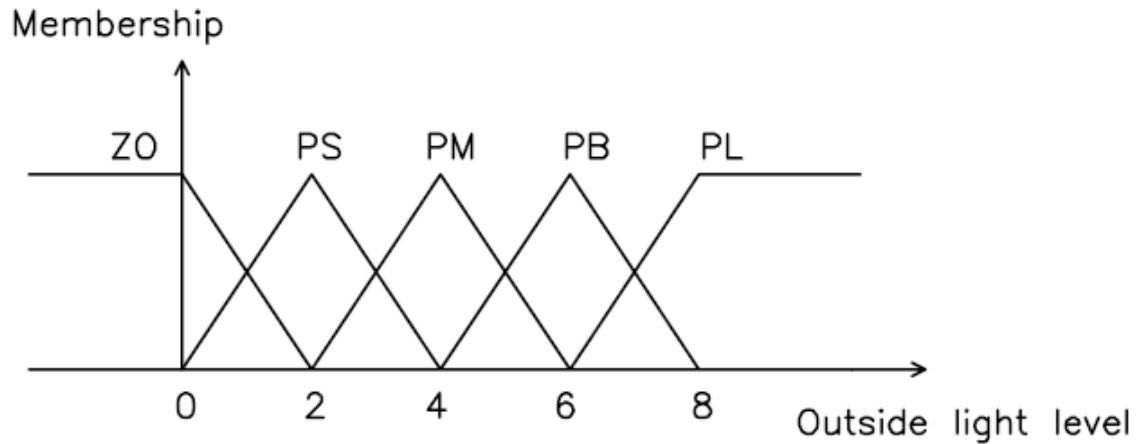


Figure 4.13 Input fuzzy sets for outside light level.

And for the output fuzzy sets:

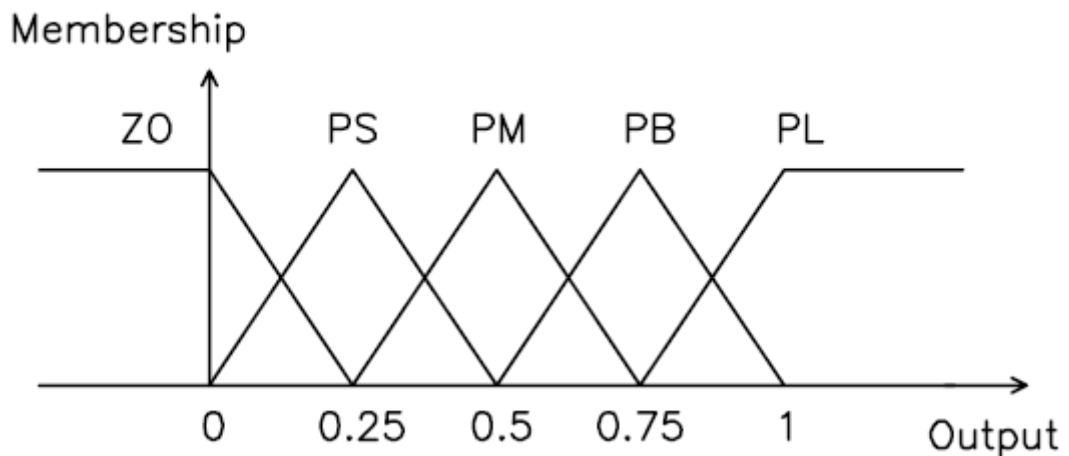


Figure 4.14 Output fuzzy sets.

The response of the control system with a step change of 1 khz results a change of 12 khz or 21% overshoot as shown in the middle of Figure 4.17. The resulting overshoot is excessive and can be reduce by adjusting the center points of the input and output fuzzy sets. The control surface of the five fuzzy sets is shown in Figure 4.15.

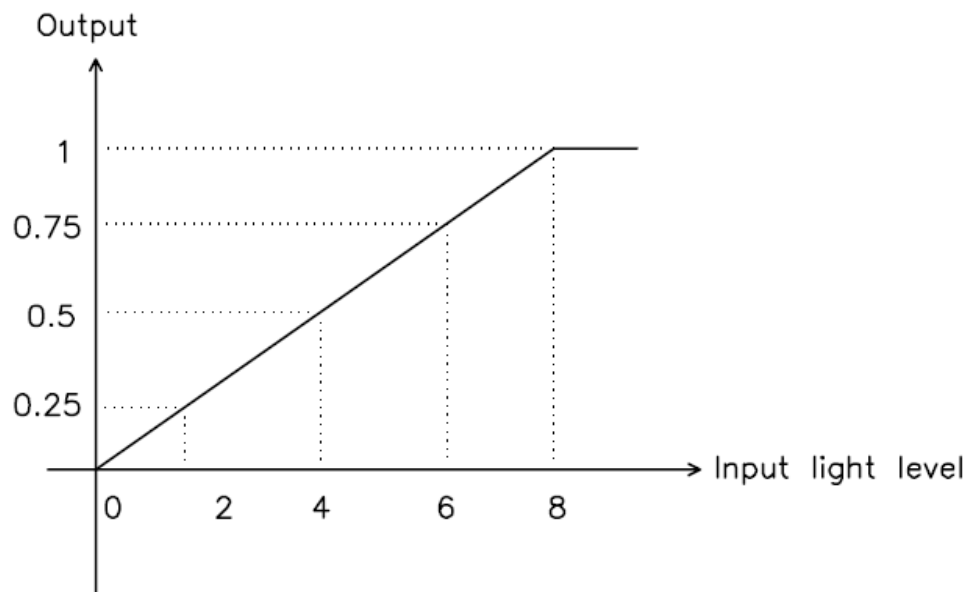


Figure 4.15 The control surface of the equally five fuzzy sets.

It can be seen from Figure 4.15 that the control surface is linear with an effective gain of 0.125. Therefore, the equally spaced input and output fuzzy sets proportional fuzzy controller is effectively a classic controller with a constant gain. The response of the control system with tweaked five fuzzy sets C (Figure 4.16) is shown in Figure 4.18.

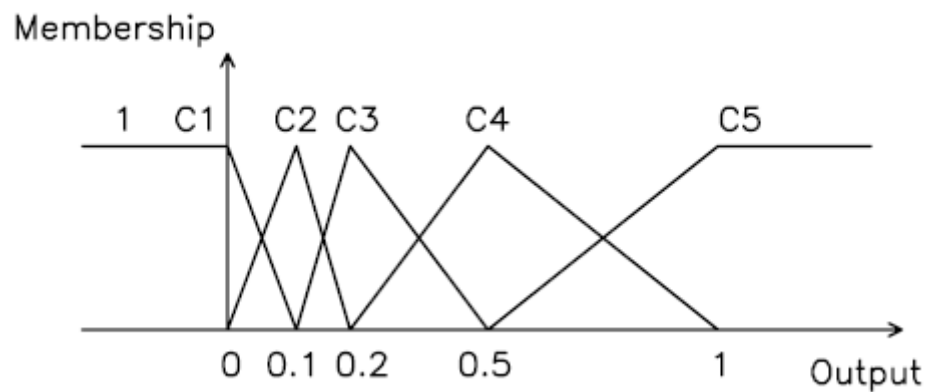


Figure 4.16 Tweaked output fuzzy sets.

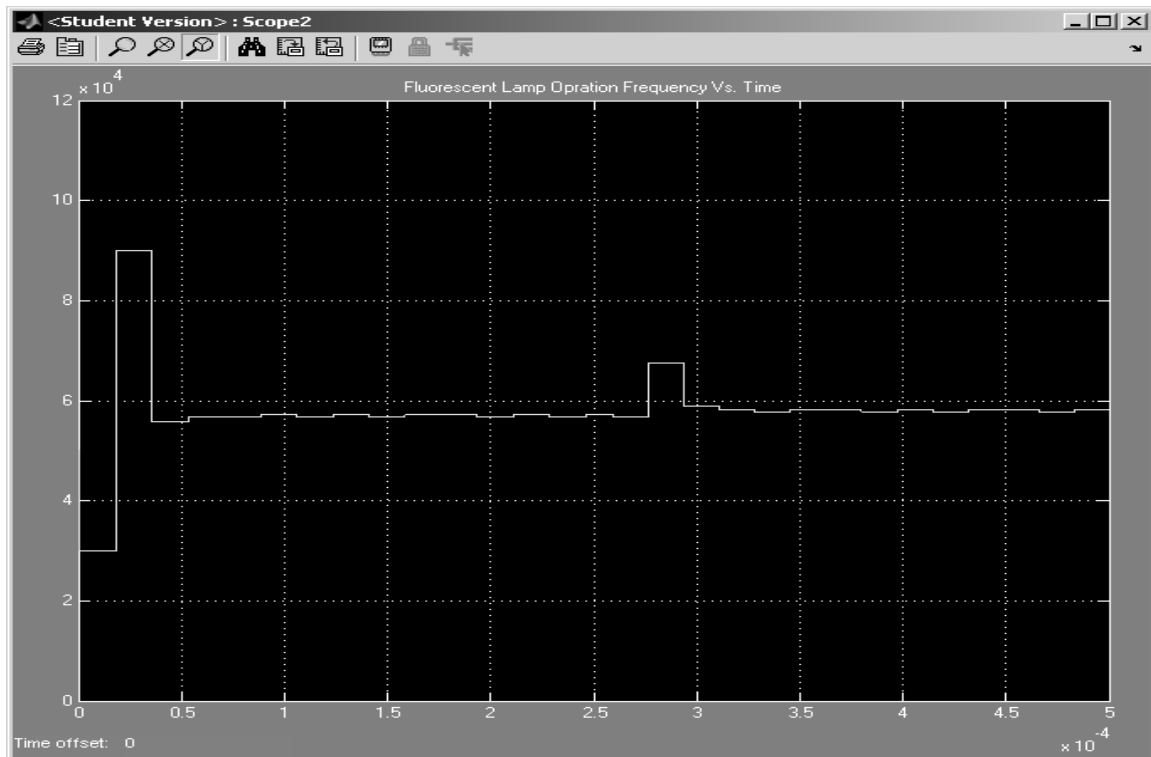


Figure 4.17 Light control system response with five fuzzy sets.

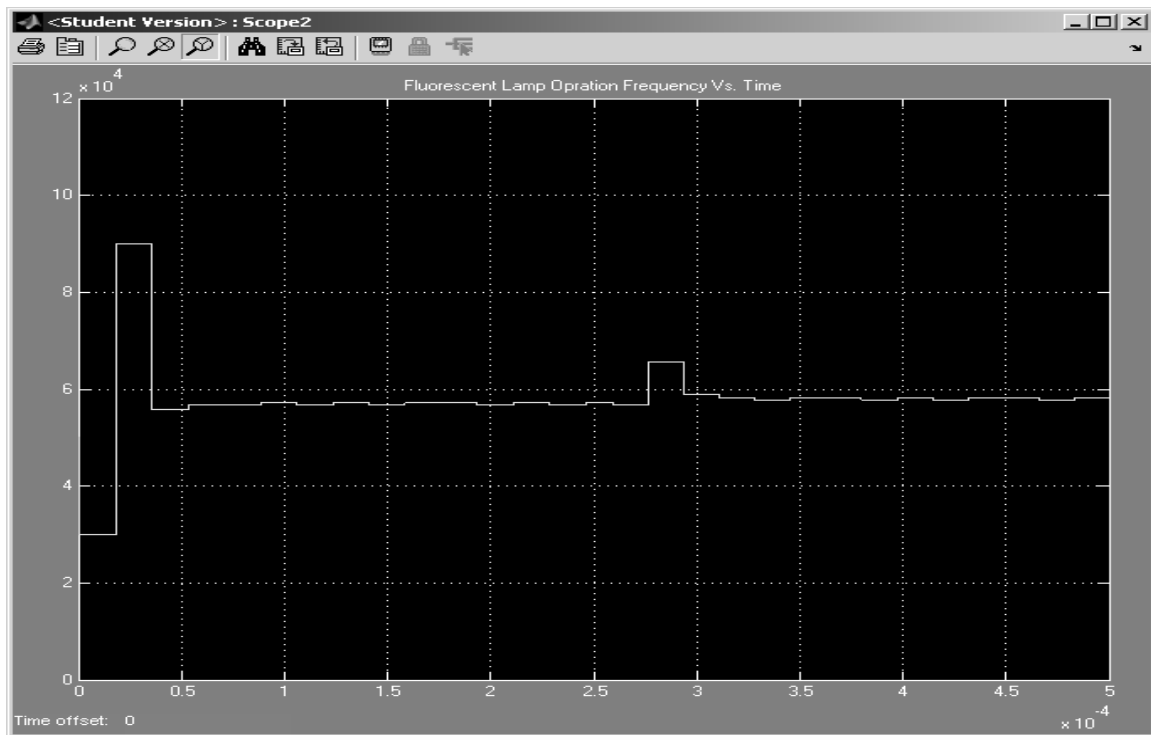


Figure 4.18 Light control system response with five tweaked fuzzy sets.

The response of the control system with seven equally spaced input and output fuzzy set shown in Figures 4.19. The fuzzy sets are shown Figure 4.21 and the rule base for this controller is:

If input is Zero then output is Zero

If input is positive Small Small then output is positive Small Small

If input is positive Small Medium then output is positive Small Medium

If input is positive Medium then output is positive Medium

If input is positive Big Medium then output is positive Big Medium

If input is positive Big then output is positive Big

If input is positive Large then output is positive Large

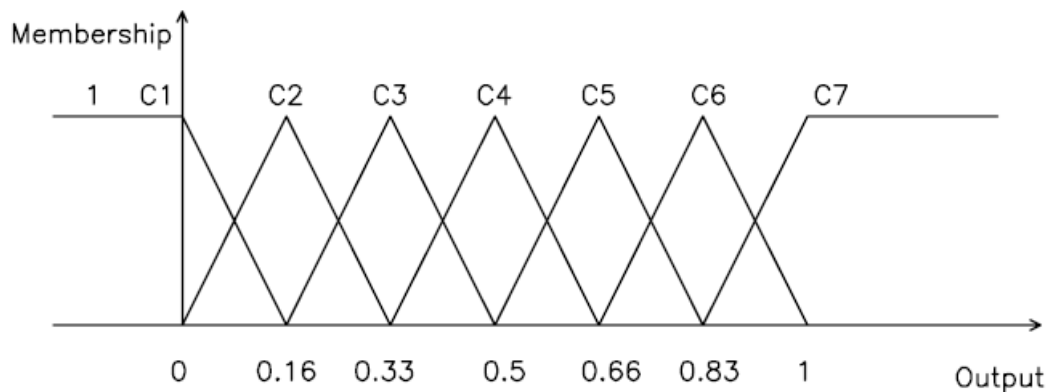
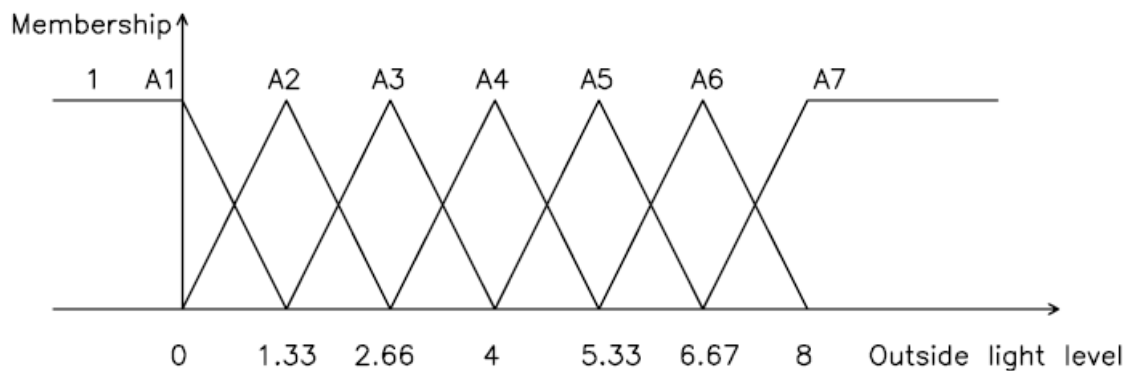


Figure 4.19 Input and output seven fuzzy sets.

It can be seen from Figure 4.21 that there is an overshoot of 14% to a step change of 1 khz in the outside light level. Note that the seven fuzzy input and output fuzzy sets fuzzy controller is equivalent to a classical controller with a gain of 0.125. The reduction in the overshoot from 21% in the case of five fuzzy set to 14% in the case of seven fuzzy sets is not due to the non linear nature of the fuzzy controller but due to the division of the light level into more fuzzy sets. As mentioned earlier, the overshoot to the step change in the input level can be decreased by adjusting the center points of the input or output fuzzy sets or both. The response of the system to a step change of 1 khz with the seven fuzzy sets shown in figure 4.20 is given in figure 4.22.

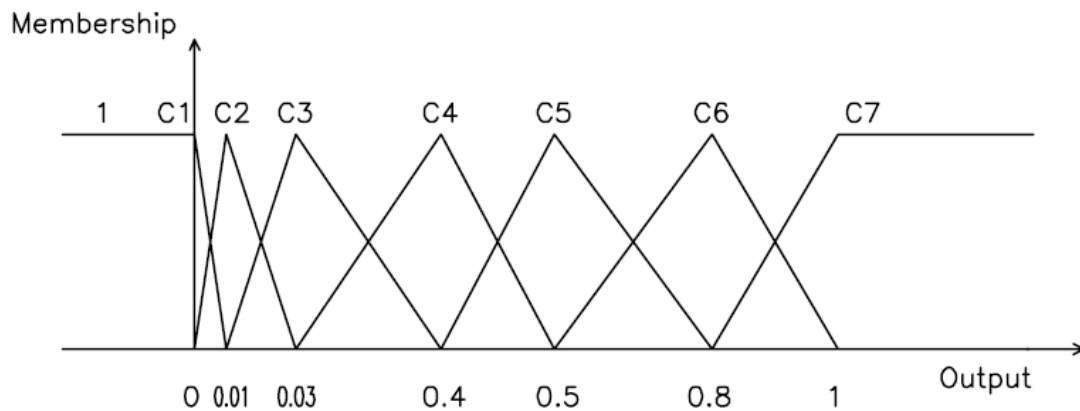


Figure 4.20 Tweaked Seven fuzzy sets for output.

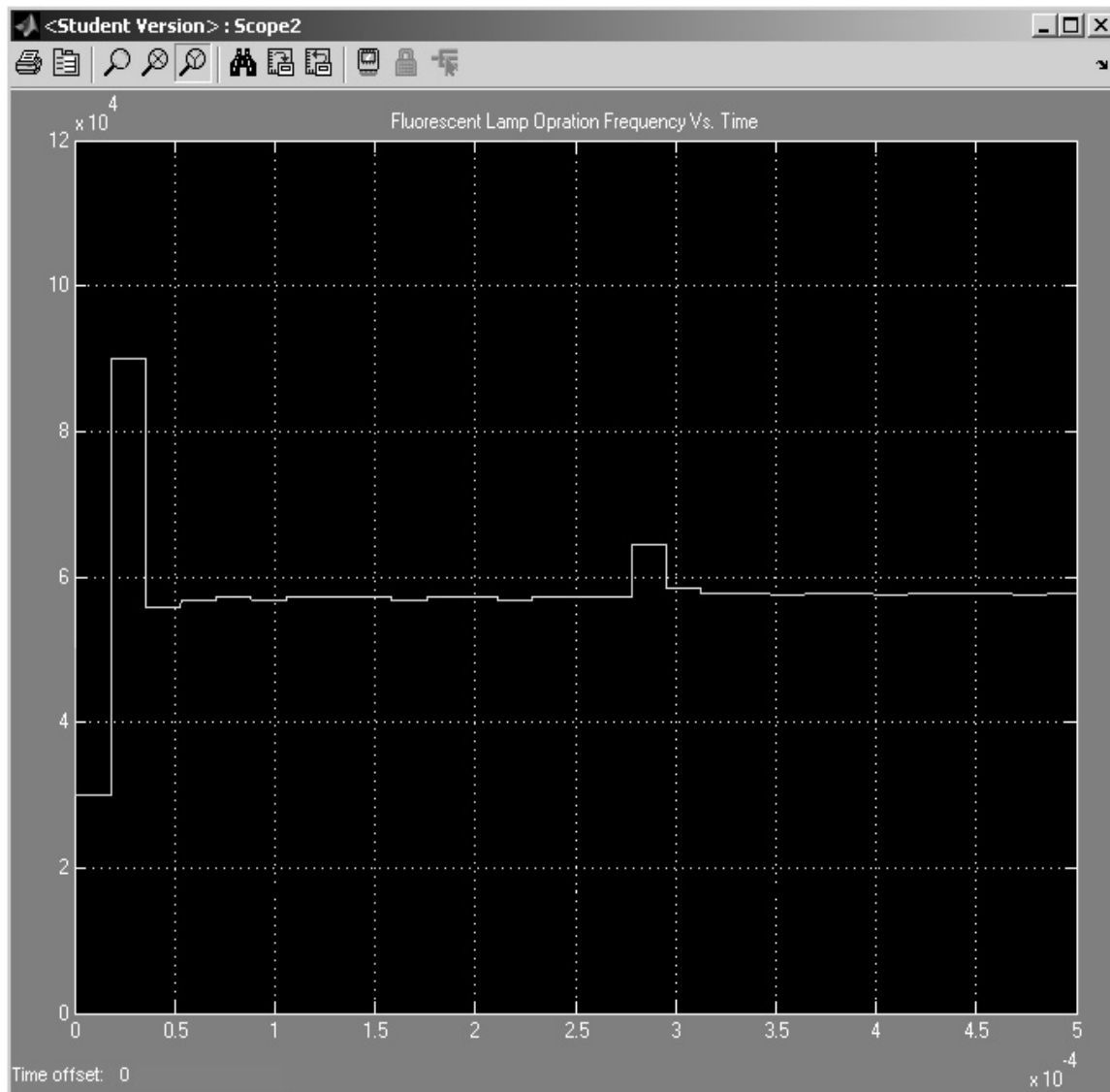


Figure 4.21 Light control system response with seven fuzzy sets.

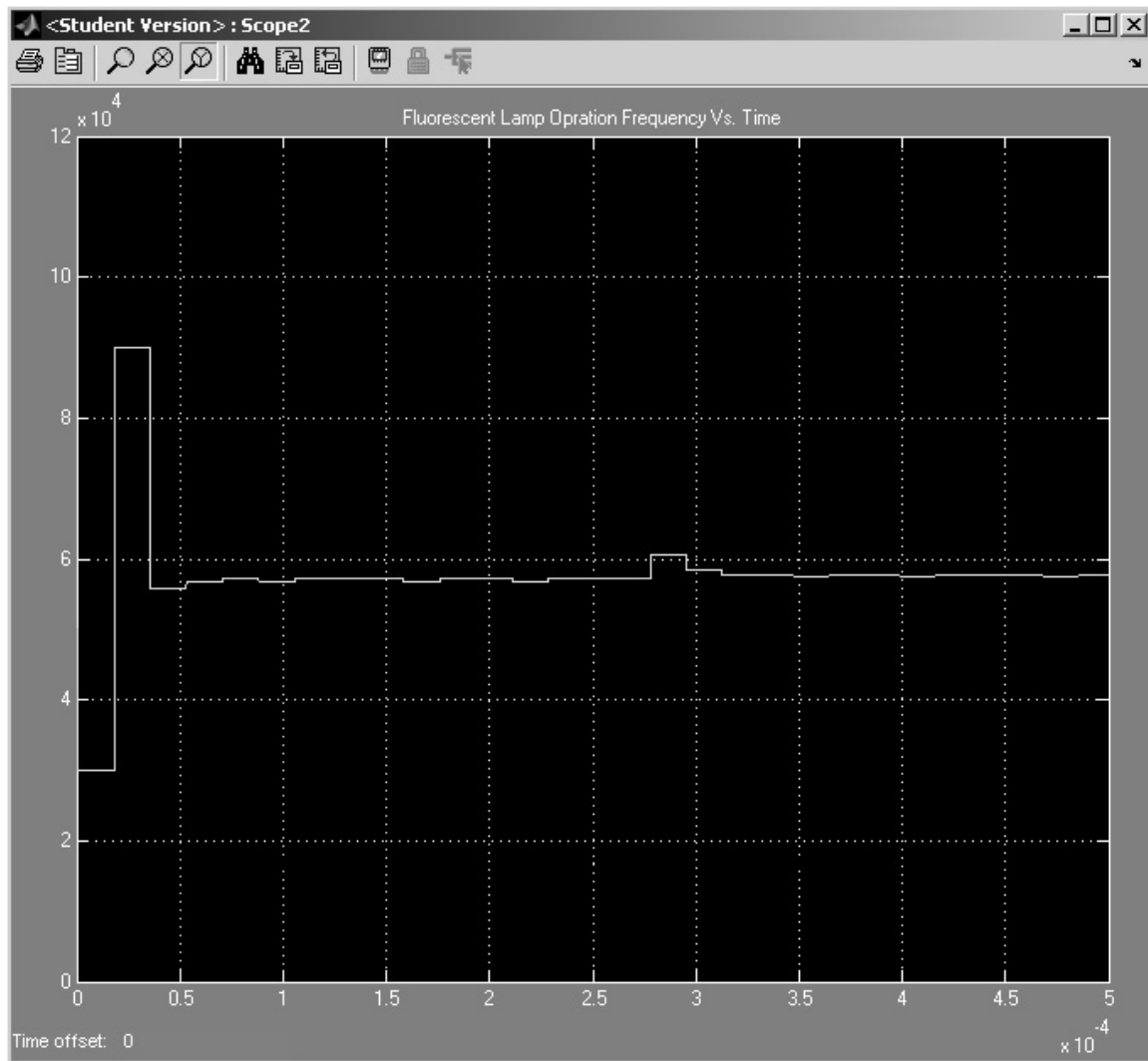


Figure 4.22 Light control system response with seven tweaked fuzzy set

The control surface for the controller with the tweaked output fuzzy set shown in Figure 4.23. It can be seen from this figure that the control surface is piecewise linear with different effective gain in different region of the controller.

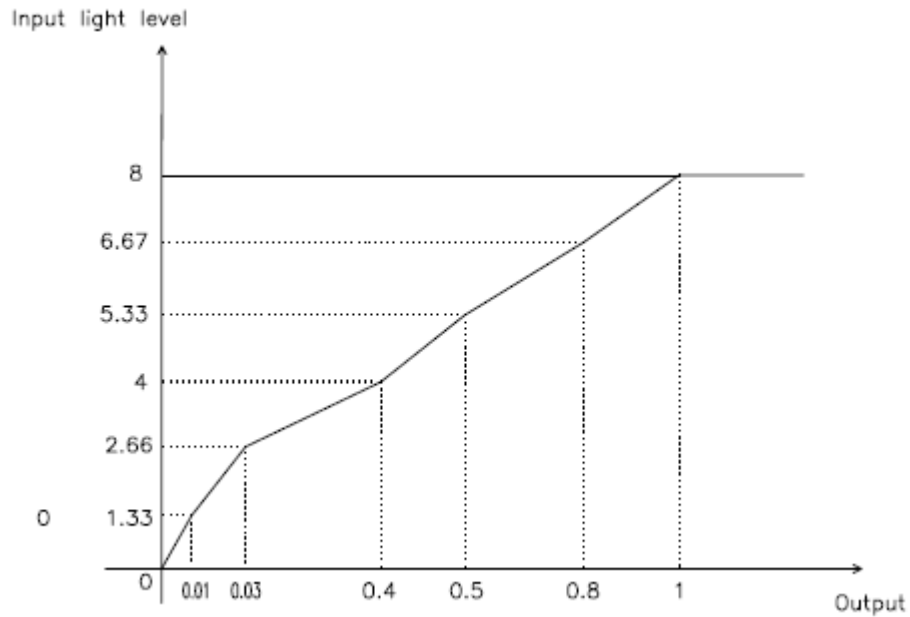


Figure 4.23 The control surface of the controller with tweaked output sets.

The response of the system with the tweaked controller has an overshoot of only 7%. It should be pointed out that the response of the system can be improved further by adjusting the center points of the output fuzzy sets, which were not drawn in this study. It should also be noted that the outside light level increases or decreases very slowly and the change of 1 khz may be the maximum change.

4.3 Summary

In this chapter, the basic ideas of fuzzy set theory are presented and the design of a fuzzy logic controller to dim fluorescent lamp is carried out. The Rule base of fuzzy logic controller is presented and the scaling of input and output of fuzzy logic controller is carried out. The response of fluorescent lamp light control

system for five input and output fuzzy sets is presented. The overshoot reduction is accomplished by manipulating of the fuzzy sets. Finally, the number of fuzzy set is increased from five to seven to reduce the overshoot.

5. Simulation Results

5.1 Simulation results

The block diagram of the lighting control system simulation in Matlab-Simulink is shown in the Figure 5.1. The fluorescent lamp and the electronic ballast have been simulated in the frequency range of 51 KHz to 91 kHz because of the fluorescent lamp and electronic ballast behaviors. The fluorescent lamp is a F32/54 T8 lamp and the electronic ballast is a Quicktronic Delux HF 2X32/200-

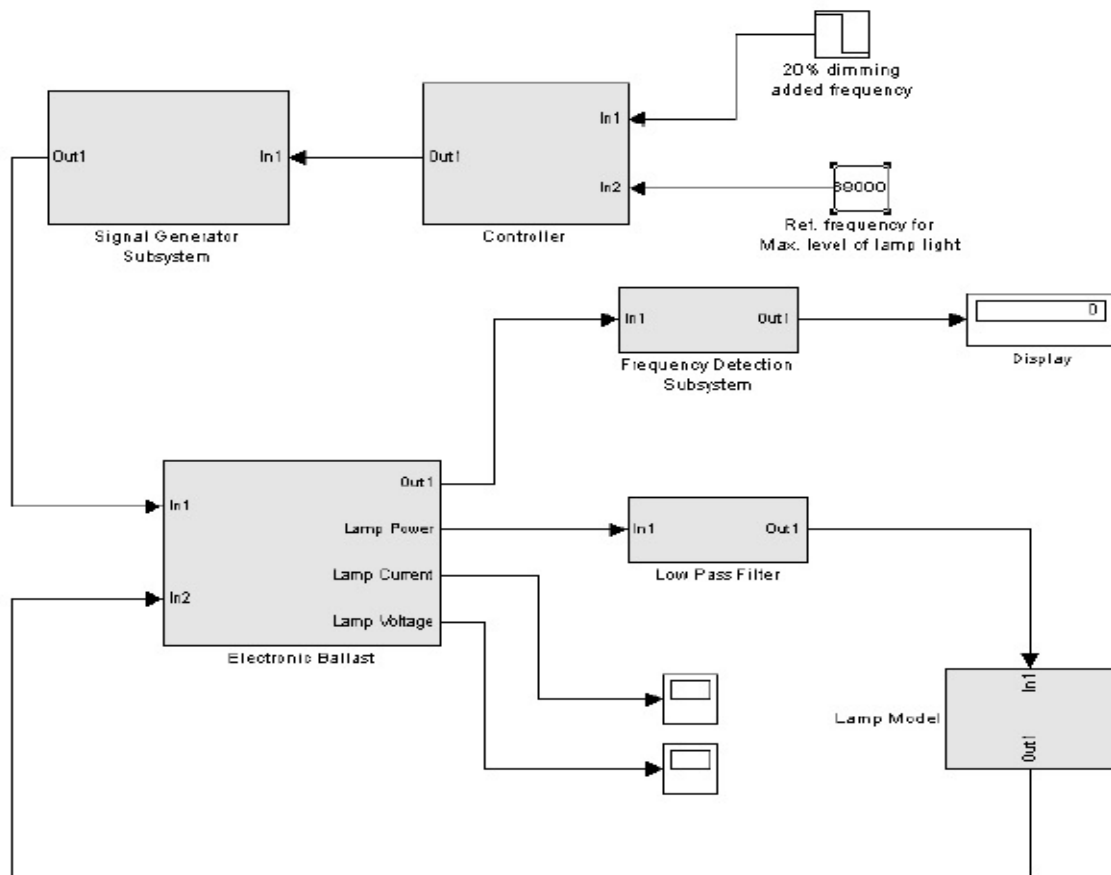


Figure 5.1 Lighting Control System Simulation.

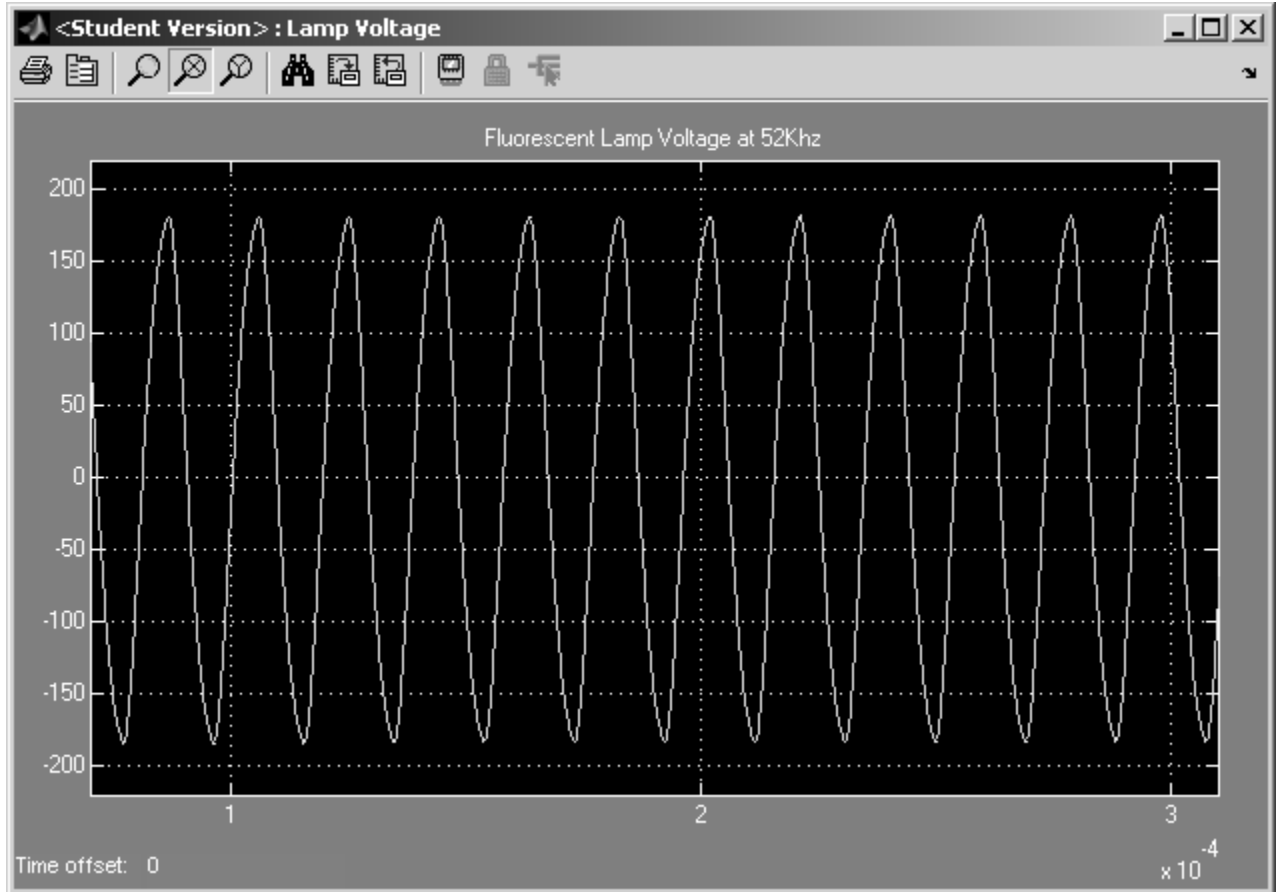


Figure 5.3 Fluorescent lamp voltage for 52 kHz electronic ballast.

For frequencies below the resonant frequency, the impedance of the electronic ballast does not decrease with the frequency as determined by the resonant circuit. In this situation, the electronic ballast is not able to dim the fluorescent lamp and thus, is the main reason for working above the resonant frequency for all electronic ballast. The Current and voltage waveforms for frequency of 40 kHz are shown in the Figures 5.4 and 5.5. It can be seen the voltage and current waveforms are still sinusoidal.

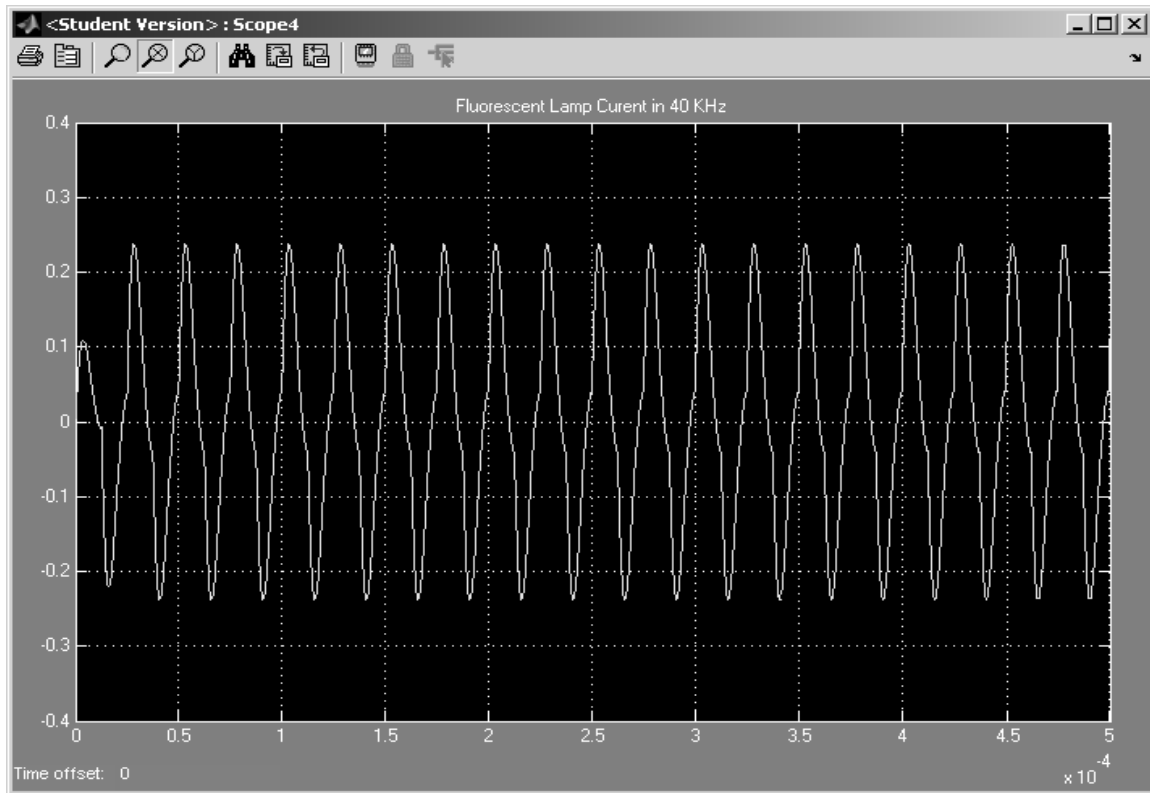


Figure 5.4 Fluorescent lamp current for 40 kHz electronic ballast.



Figure 5.5 Fluorescent lamp voltage for 40 kHz electronic ballast.

Figure 5.6 shows fluorescent lamp current waveform in frequency of 30 kHz. It can be seen from the figure that the fluorescent lamp current waveform has some disturbances. Since the electronic ballast and fluorescent lamp are working below the resonant frequency, the frequency detection subsystem does not work properly. Frequency detection subsystem works based on zero crossing points of fluorescent lamp current or voltage waveform. For a period of the current or voltage waveform, there are more than 3 zero crossing points and the frequency detection subsystem is not able to detect the correct frequency.



Figure 5.6 Fluorescent lamp Current for 30 kHz electronic ballast.

Figures 5.7 and 5.8 shows the fluorescent lamp voltage and current when a change of 1 khz step function in frequency is applied to the lighting control system. In these two figures, a positive step function applied means the light sensor detects more light and increases the frequency. An increase in the input frequency increases impedance of the electronic ballast and hence the current is decreased. Figure 5.8 shows that there is a very little change in the fluorescent lamp voltage with the change in frequency.



Figure 5.7 Fluorescent lamp current with applying of a positive step function.

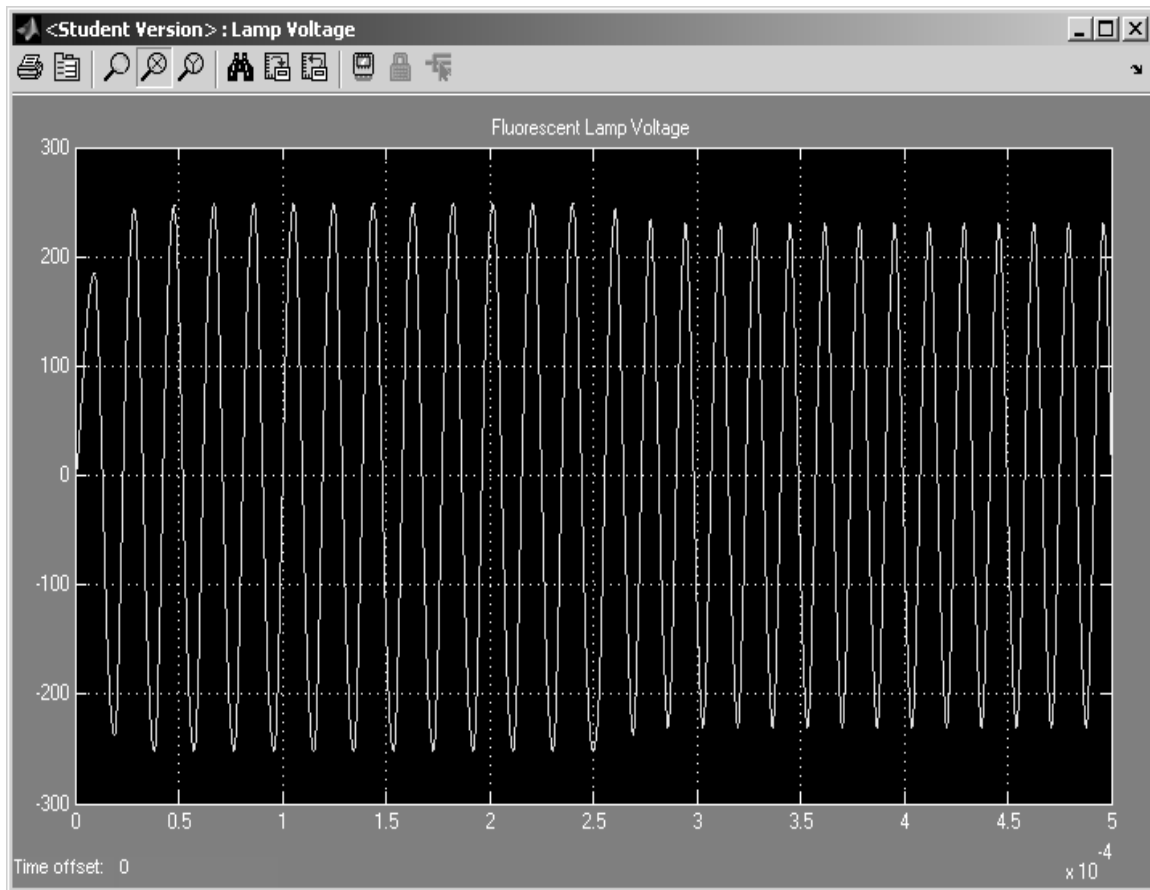


Figure 5.8 Fluorescent lamp Voltage with applying of a positive step function.

Fluorescent lamp current and voltage waveforms for a negative step change in frequency are shown in the Figures 5.9 and 5.10. This is the result of a reduction in outside light and the output frequency of the light sensor is decreased. With a decrease in the frequency of electronic ballast, its impedance is decreased and the fluorescent lamp current is increased.



Figure 5.9 Fluorescent lamp current with applying of a negative step function.



Figure 5.10 Fluorescent lamp Voltage with applying of a negative step function.

As an example, Table 5.1 shows the dimming percent of the fluorescent lamp over half of a sunny day in a typical office. The total wattage of a regular fluorescent lamp is 32 watt and table 5-1 shows the wattage that can be saved by using the fluorescent light control system. It can be seen from the table in some area that dimming of fluorescent lamp is more than 50 percent the saved wattage is more than 25 percent of fluorescent total watt.

Table 5.1 Percent of saved energy in different dimming percent.

Dimming percent	Time	I_{lamp} (Average) (Amp.)	V_{lamp} (Average) (Volt)	P_{lamp} (W) (Average) Out of 32W	Energy Saving (W)
0% (52khz)	before 8a.m after 6p.m	0.289	99.2	28.67	—
10% (56khz)	8a.m–9a.m	0.258	103.18	26.6	2.07
30% (64khz)	9a.m–10a.m	0.212	106.74	22.62	6.05
50% (72khz)	10a.m–11a.m	0.182	113.21	20.6	8.07
80% (84khz)	11a.m–12a.m	0.113	126.67	14.14	14.53
100% (91khz)	Noon	0.042	143.9	6.04	22.64

The table 5.1 also, shows the results for a sunny day obtained using different outside light level. Note that these results are for one of the 32 W fluorescent lamp in a typical office fixture (containing three lamps). Table 5.1 shows that dimming regimen in the morning because the regimen in the afternoon is similar to the morning regimen. It can also be seen from this table

that the total power saved is about 53 watts and hence a total saving of 159 watts for a three lamp fixture and, the kilowatt energy saving per month is 76.32 kilowatt Dayton Power and Light as one of the energy provider in Ohio offers 7 cents for a kilowatt energy. Based on this rate, the net saving in kilowatt energy in a month for a typical office is about \$6. Considering that there are many offices in a typical building, the resulting saving could be substantial.

5.2 Summary

In this chapter, the simulation result of the fluorescent lamp current and voltage are shown. The main reason for using the electronic ballasts above their resonant frequency are explained. The simulation results show that below the resonant frequency, the frequency detection subsystem of electronic ballast malfunction. A negative step function in frequency of the system from a decrease in outside light and a positive step function results from an increase in outside light. The fluorescent lamp voltage and current are shown for this case. At the end of chapter, an example to understand how much energy is saved with a fluorescent light control system is presented.

6. Summary and Conclusion

6.1 Summary and conclusions

In this thesis, the design of a simple low cost lighting control system for a typical office with fluorescent lamps is presented. The light control system components and operation are discussed and the simulation of a complete fluorescent lamp system (fluorescent lamp and electronic ballast) along with light sensor is carried out.

Simulation of the fluorescent lamp is carried out based on the experimental data for voltage, current and power of the fluorescent lamp. Experimental data is plotted and the Levenberg-Marquardt (LMA) curve fitting algorithm is used to fit a mathematical equation to the experimental data. This mathematical equation is then used to develop a Matlab-Simulink model for fluorescent lamp.

Simulation of the electronic ballast is carried out using a typical half-bridge series resonant circuit. First, the values of the components used are calculated based on the operation of the system above the resonant frequency. The Matlab-Simulink model of the electronic ballast is then connected to the model of the fluorescent lamp and the simulation of the complete system is carried out. The results are compared with the experimental data used for the simulation.

The electronic circuit of a typical light sensor is presented and the simulation using the resistance-light characteristic of the light sensor is carried out. A subsystem to detect the frequency of the fluorescent lamp current or voltage is designed. Finally, a subsystem to generate the desired frequency using the fuzzy controller is presented in chapter 4. The complete simulation model connecting all the components is developed and the simulations are carried out. The results obtained follow the experimental data very closely.

The control of the fluorescent lamp light system using a fuzzy logic controller is presented. First, the mathematical foundation of the fuzzy logic is briefly discussed. The structure of a fuzzy logic controller is presented and all its components are discussed. The implementation of a fuzzy logic controller is explained by using an example. These fuzzy logic concepts are then used to design a proportional fuzzy logic controller (PFLC) for the fluorescent lamp light control system. Based on the knowledge of the fluorescent lamp light system, a rule-base for the PFLC is developed. The domain of the input and output fuzzy sets for the PFLC are specified based on the fluorescent lamp system and the human visibility frequency range. The Matlab-Simulink program for the PFLC is carried out and the response of the closed-loop control system is obtained. The fuzzy sets are tuned experimentally to improve the response of the fluorescent lamp light system. Simulations are also carried out by increasing the number of fuzzy sets and the results are presented.

Dimming the fluorescent lamp by 50% results in a saving of 25% of the lamp's total wattage. It was shown that the total energy saved is about 53 watts

and hence a total saving of 159 watts for a three lamp fixture or about \$6 per month for a typical three lamp fixture. Considering that there are many offices in a typical building, the resulting saving could be substantial.

6.2 Recommendation for future work

Lighting control system for a typical office discussed in this thesis used light sensor installed in the window frame to catch the outside light for light harvesting. Putting a light sensor over the office computer or on the work station may be a better design. In addition, extending the light control system to control the light level over a control zone with multiple offices may be beneficial in saving cost.

Appendices

Appendix A

Matlab Programs

% This program calculates coefficients of equation 3-1 based on Levenberg-Marquardt Algorithm (LMA)

```
xdata = (1:.01:30)';  
ydata = [(8000 * exp(-.2 * xdata))+(2000 * exp(-.05 * xdata))] +  
randn(size(xdata));  
[estimates, model] = fitcurvedemo(xdata,ydata)  
function [estimates, model] = fitcurvedemo(xdata, ydata)  
% Call fminsearch with a random starting point.  
start_point = rand(1, 4);  
model = @expfun;  
estimates = fminsearch(model, start_point);  
% expfun accepts curve parameters as inputs, and outputs sse,  
% the sum of squares error for [(A * exp(B * xdata))+(C .* exp(D * xdata))] -  
ydata,  
% and the FittedCurve. FMINSEARCH only needs sse,  
% plot the FittedCurve at the end.  
function [sse, FittedCurve] = expfun(params)
```

```

    A = params(1);
    B = params(2);
    C = params(3);
    D = params(4);
    FittedCurve = [(A .* exp(B * xdata))+(C .* exp(D * xdata))];
    ErrorVector = FittedCurve - ydata;
    sse = sum(ErrorVector .^ 2);
end
end

% This function returns the membership of the input in the specified fuzzy sets.
% Gives zero as output for input with no memberships.
function [y] = fuzzify(x,cp)

len= length(cp);
y=zeros(1,len);
p=floor(len/2);
flag=0;
if x>cp(len)
    y(len)=1;
elseif x<cp(1)
    y(1)=1;
else
    if x>cp(p),
        while x>cp(p)

```

```
p=p+1;
```

```
end
```

```
p=p-1;
```

```
flag= 1;
```

```
end
```

```
if flag==0
```

```
    while x<cp(p)
```

```
        p=p-1;
```

```
    end
```

```
end
```

```
ub=cp(p+1);
```

```
mem= (x-ub)/(cp(p)-ub);
```

```
y(p)=mem;
```

```
y(p+1)= 1-mem;
```

```
end
```

% This function returns the index of the first non-zero membership value and also returns the 2 membership values.

```
function [p,y] = fuzzify(x, cp)
```

```
len= length(cp);
```

```
y=zeros(1,len);
```

```

p=floor(len/2);
flag=0;
y=[];
if x==cp(p)
    p1=p-1;
    flag=2;
end
if x>cp(len)
    y(2)=1;
    p=len-1;
elseif x<cp(1)
    y=[1 0];
    p=1;
else
    if x>cp(p),
        while x>cp(p)
            p=p+1;
        end
    p=p-1;
flag= 1;
end
if flag==0
    while x<cp(p)

```

```

        p=p-1;
    end
end

ub=cp(p+1);
mem= (x-ub)/(cp(p)-ub);
y(1)=mem;
y(2)= 1-mem;
end

if flag==2
    p=p1;
    y=[0 1];
end

```

% this function uses fuzzify2 function to calculate the output. Obtains the required indices from the fuzzify2 function.

```

function k = pflc(e,cp,rv)
[p,tv] = fuzzify2(e,cp);
k= tv*[rv(p),rv(p+1)]

```

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